# “STUDY OF SOFT SWITCHING CONVERTER FOR SWITCHED RELUCTANCE MOTOR DRIVE”

**A Thesis Report Submitted In Partial Fulfillment of The**

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**MASTER OF ENGINEERING**

**In**

**Power System and Electric Drives**
**(P.S.E.D)**

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# CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled "**Study of Soft-Switching Converter for Switched Reluctance Motor Drive**", in partial fulfilment of the requirement of the award of degree of Master of Engineering in **Power Systems & Electric Drives** submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Mr. Souvik Ganguli**, Asstt. Prof, EIED.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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# ABSTRACT

Switched reluctance motor (SRM) has become a competitive selection for many applications of electric machine drive systems recently due to its relative simple construction and its robustness. The advantages of those motors are high reliability, easy maintenance and good performance. The absence of permanent magnets and windings in rotor gives possibility to achieve very high speeds (over 10000 rpm) and turned SRM into perfect solution for operation in hard conditions like presence of vibrations or impacts. Such simple mechanical structure greatly reduces its price. Due to these features, SRM drives are used more and more into aerospace, automotive and home applications. The major drawbacks of the SRM are the complicated algorithm to control it due to the high degree of nonlinearity, also the SRM has always to be electronically commutated and the need of a shaft position sensor to detect the shaft position, the other limitations are strong torque ripple and acoustic noise effects.

The purpose of the thesis is to design, develop, implement a soft switching converter topology using insulated gate bipolar transistor (IGBT) suitable for switched reluctance motor. Research being done in field of switched reluctance motor including soft switching converter is discussed. The validity of the topology is verified through MATLAB simulation. Results are presented and comparison is made between converter topology using metal oxide semiconductor field effect transistor (MOSFET) and converter topology using insulated gate bipolar transistor (IGBT). Conclusions are drawn regarding the effectiveness of proposed converter topology. The novel topology is presented and the principle of operation is described in detail.

The use of insulated gate bipolar transistor (IGBT) have enabled better switching performance than the metal oxide semiconductor field effect transistor (MOSFET) in medium to high power applications due to their lower on-state power loss and high current densities.

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# NOMENCLATURE

| ABBREVIATION | MEANING |
|---|---|
| SRM | Switched Reluctance Motor |
| LSRM | Linear Switched Reluctance Motor |
| SSC | Soft Switching Converters |
| ZCS | Zero Current Switching |
| ZVS | Zero Voltage Switching |
| ZVT | Zero Voltage Transition |
| ZVSCV | Zero Voltage Switching Clamped Voltage Converters |
| AQRDCL | Auxiliary Quasi-Resonant DC Link |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| IGBT | Insulated Gate Bipolar Transistor |

# CHAPTER 1

# SWITCHED RELUCTANCE MOTOR AND THEIR OPERATION

In this chapter, we first introduce the mechanical structures of typical SR motor. Then, the electromechanical coupling in an SR motor, i.e., the principle of torque production, is described. The basic characteristics of electrical hardware used for SRM are introduced and finally the various configurations of switched reluctance motor are introduced.

## 1.1 INTRODUCTION

The switched reluctance motor (SRM) drives for industrial applications are of recent origin. Key to an understanding of any machine is its torque expression, which is derived from first principles. The implications of machine operation and its salient features are inferred from the torque expression [1]. The torque expression requires a relationship between machine flux linkages or inductance and the rotor position. The switched reluctance motor (SRM) is a synchronous machine. It has wound field coils as in a DC motor for the stator windings. The rotor however has no magnets or coils attached. The rotor of the motor becomes aligned as soon as the opposite poles of the stator become energized. In order to achieve a full rotation of the motor, the windings must be energized in the correct sequence.

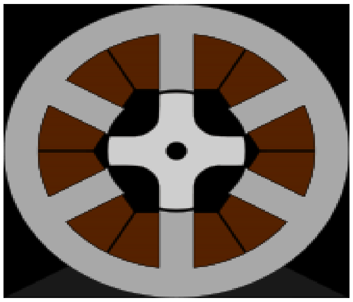


**Figure 1.1: Switched Reluctance Motor**

**S**witched reluctance motor (SRM) is advantageous due to it's the simple construction, low manufacturing cost, and high torque density. Recently, its application has been widely spread from industrial to home appliance. However, SRM causes acoustic noise and vibration due to the torque ripples. The torque ripples can be reduced by means of the geometric motor shape design and the electric control. SRM needs a high input voltage, current, and phase inductance to get high torque [1, 2].

But, SRM uses a capacitor with low capacitance in the rectifier of a drive circuit because of the cost and its size. This causes ripples generated in the dc link voltage. Due to these ripples, the performance of the motor such as torque ripples and a radial force on the surface of the pole is degraded. Therefore, these kinds of conditions must be considered in analysis. When the switch turns off, the phase current flows through the freewheeling diodes or the capacitor of dc link. Generally, freewheeling diodes and dc link voltage ripples have not been considered when the motor is analyzed. The time stepped voltage source finite element method (FEM) is used as the computational method to analyze the SRM, considering freewheeling diodes and dc link voltage ripples.

## 1.2 OPERATION

The reluctance motor is an electric motor in which torque is produced by the tendency of its moveable part to move to a position where the inductance of the excited winding is maximized. The origin of the reluctance motor can be traced back to 1842, but the “reinvention” has been possibly due to the advent of inexpensive, high-power switching devices.

The reluctance motor is a type of synchronous machine. It has wound field coils of a DC motor for its stator windings and has no coils or magnets on its rotor. Fig.1.2 shows its typical structure of 6/4 and 8/6 poles. It can be seen that both the stator and rotor have salient poles; hence, the machine is a doubly salient machine. The rotor is aligned whenever the diametrically opposite stator poles are excited [4].

In a magnetic circuit, the rotating part prefers to come to the minimum reluctance position at the instance of excitation. While two rotor poles are aligned to the two stator poles, another set of rotor poles is out of alignment with respect to a different set of stator poles. Then, this set of stator poles is excited to bring the rotor poles into alignment. This elementary operation can be explained by Fig. 1.3. In the figure, consider that the rotor poles $r_1$ and $r_1'$ and stator poles c and c′ are aligned.

Apply a current to phase a with the current direction as shown in Fig. 1.3a. A flux is established through stator poles a and a′ and rotor poles $r_2$ and $r_2'$ which tends to pull the rotor poles $r_2$ and $r_2'$ toward the stator poles a and a′, respectively.

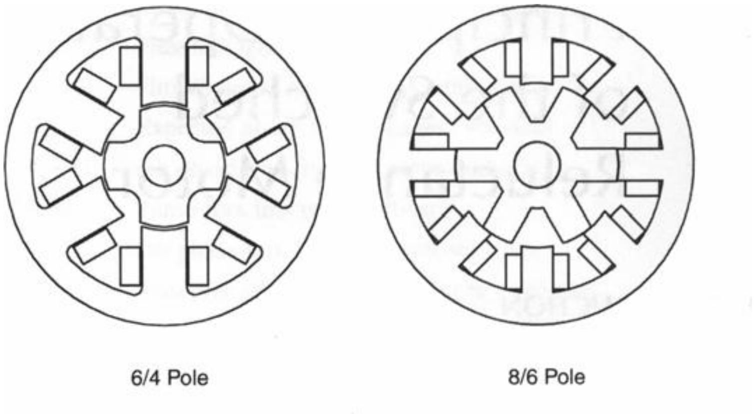
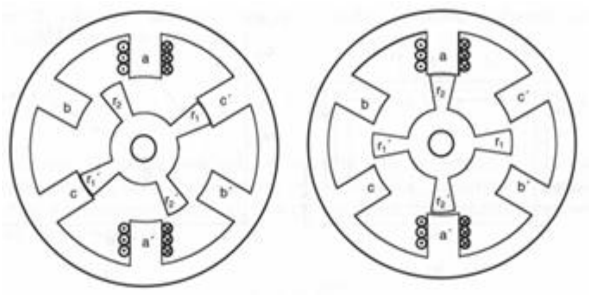


**Figure 1.2: SRM with 6/4 and 8/6 Poles**

When they are aligned, the stator current of phase a is turned off and the corresponding situation is shown in Fig. 1.3b.

Now the stator winding b is excited, pulling $r_1$ and $r_1'$ toward b and b′, respectively, in a clockwise direction. Likewise, energizing phase c winding results in the alignment of $r_2$ and $r_2'$ with c and c′, respectively [4]. Accordingly, by switching the stator currents in such a sequence, the rotor is rotated. Similarly, the switching of current in the sequence of acb will result in the reversal of rotor rotation. Since the movement of the rotor, hence the production of torque and power, involves a switching of currents into stator windings when there is a variation of reluctance, this variable speed motor is referred to as a switched reluctance motor (SRM).



**(a)** **(b)**

**Figure 1.3: Operation of an SRM (a) Phase c Aligned (b) Phase a Aligned.**

## 1.3 PRINCIPLE OF TORQUE PRODUCTION

Like many other electrical machines, an SR machine is an energy converter that takes electrical energy and produces mechanical energy in motoring operation, and vice versa in generating operation. The energy is stored in the magnetic field created by the phase windings and is exchanged between the electrical and the mechanical subsystems. In the following, the process of torque production in an SR machine is described [3].

When a phase is excited by applying a voltage across its concentrated coil, the current in the coil creates a magnetic flux through its stator poles. The magnetic flux flows through the pair of nearest rotor poles, travels in the rotor and stator steel, and closes a magnetic circuit, as shown in Fig. 1.4. In a magnetic circuit, there exists magnetic reluctance.

It is analogous to resistance in an electrical circuit and depends on the magnetic permeability of the material that the flux flows through. In the case of an SR machine, the reluctance in the air gap between the stator and rotor poles is very large compared to that in steel.

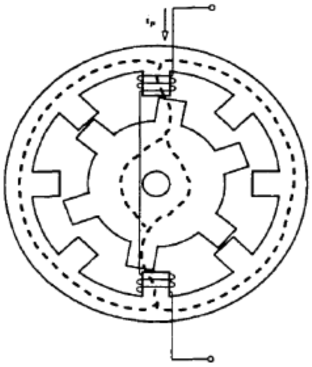


**Figure 1.4: Magnetic Circuit in a SR Machine**

The total reluctance of the magnetic circuit can be well approximated by the reluctance of the air gap.

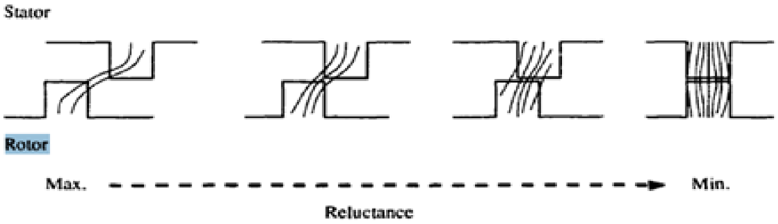


**Figure 1.5: Variation of Reluctance with Respect to Rotor Position**

Because of the doubly salient geometry of an SR machine, the distance between the stator and rotor poles changes as the rotor rotates, and hence the reluctance of a flux path varies as shown in Fig. 1.5.

A phase is in the unaligned position when the interpolar axis of the rotor Fig. 1.6 is aligned with the stator poles of the phase [3]. The reluctance of the flux path is at its minimum in the aligned position and is at its maximum in the unaligned position. The variable reluctance principle is the tendency of the rotor to align itself to the minimum reluctance position. When a phase is excited, the pair of nearest rotor poles (part of the magnetic circuit) is attracted to align themselves to the excited stator poles. Thus, torque is produced. This principle is different from the magnetic interaction occurring in other electrical machines, such as permanent magnet motors and induction motors. The torque production in these other types of motor is based on the attraction between the North and South magnetic poles of permanent or electrically induced magnets. Notice that the rotor poles of an SR machine do not require the existence of magnetic poles to produce torque. Interestingly enough, the radial magnetic attraction that operates an SR machine can become ten times larger than the circumference forces produced by an induction machine position

In the aligned position shown in Fig. 1.6.  There is no torque produced, even when the phase is energized, because the reluctance of the flux path is at its minimum. Hence, it is a stable equilibrium position. There is also no torque produced in the unaligned position because the stator pole is exactly in the middle of two adjacent rotor poles. However, as soon as the rotor is displaced to either side of the unaligned position, there appears a torque that displaces it even further and attracts it towards the next aligned position [3].

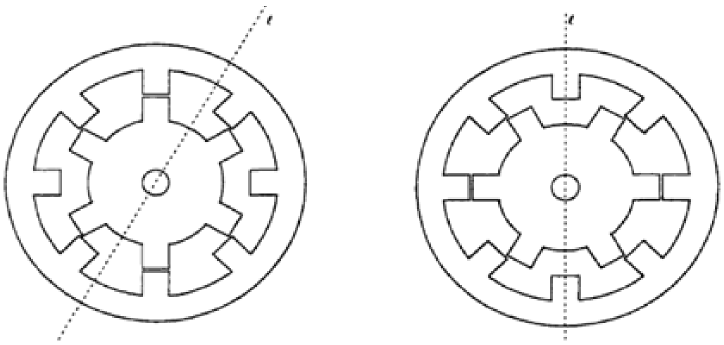


**Figure 1.6: Aligned and Unaligned Positions**

Hence, the unaligned position is an unstable equilibrium position. Consequently, torque is produced in the direction from any unaligned position to the next aligned position. Since the rotor poles are identical around the rotor, the torque production is periodic.

Also torque $T_e$

$$T_e = \frac{dL(\theta,i)}{d\theta} \cdot \frac{i^2}{2}$$

- The torque is proportional to the square of the current; hence the current can be unipolar to produce unidirectional torque. Note that this is quite contrary to the case for ac machines. This unipolar current requirement has a distinct advantage in that only one power switch is required for control of current in a phase winding. Such a feature greatly reduces the number of power switches in the converter and thereby makes the drive economical [10].
- Since the torque is proportional to the square of the current, this machine resembles a dc series motor; hence, it has a good starting torque.
- The direction of rotation can be reversed by changing the sequence of stator excitation, which is a simple operation
- Torque and speed control is achieved with converter control.
- This machine requires a controllable converter for its operation and cannot be operated directly from three-phase line supply. Hence, for constant speed applications, this motor drive is expensive in comparison to induction and synchronous motors.
- Because of its dependence on a power converter for its functioning, this motor drive is an inherently variable-speed motor drive system. There is very little mutual inductance between machine phase windings in SRM, and for all practical purposes it is considered to be negligible. Since mutual coupling is absent, each phase is electrically independent of other phases [10]. This is a feature unique to this machine only. Due to this feature, note that a short-circuit fault in one phase winding has no effect on other phases. For one thing, it makes possible operation of other healthy phases of the machine and their operation will not be derated, as the voltage requirement is the same before and after the fault. Such independence of machine phases has tremendous consequence in aircraft actuators and generators, actuators used in defense applications, motors used in coolant pumps in nuclear power plants, and traction and electric vehicles.

## 1.4 ELECTRICAL HARDWARE

SR machines utilize power converter switching circuits for the commutation of phase excitation. The most common configuration of a switching circuit is shown in Fig. 1.7. In general, a switching circuit for an SR machine is simple because of the unipolar (Not alternating) characteristic of its flux-linkage and phase current [3]. Since the direction of rotation does not depend on the signs of flux-linkage and phase current, a switching circuit of an SR machine is designed so that the current in the excitation coil flows only in one direction. In the following, we illustrate the main requirements that a switching circuit for an SR machine must satisfy. SR machines cannot operate directly from an AC or DC mains voltage supply because inputs to their phase windings must be current pulses. A power converter must supply unipolar current pulses from a DC voltage source, precisely at desired rotor positions. It must also regulate the magnitude and even waveform of the current in order to satisfy the requirements of torque and speed control and ensure safe operation of the motor and the power transistors. Finally, it must be able to supply pulses of reverse voltage for defluxing, i.e., forcing the phase current to zero in order to avoid reverse torque at certain rotor positions.

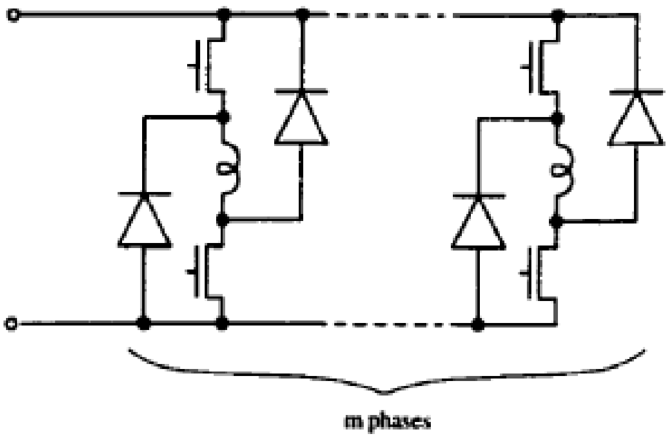
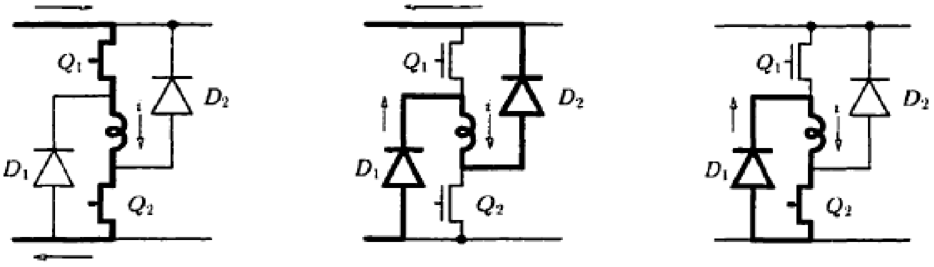


**Figure 1.7: Typical Configuration of Power Converter**

The desirable type of power converter has separate switches for each phase so that al1 phases are virtually independent of each other. The switching circuit considered in this research has the configuration in Fig. 1.8. The excitation coil in each phase is connected to one common DC voltage source (or a rectified AC supply) through a transistor switch on each end. The circuit has two freewheeling diodes to provide the unipolar characteristic of phase current. Fig. 1.8 shows the current flow in the switching circuit for one phase under different switching conditions.



(a) Q1 & Q2 on (b) D1 & D2 on (c) Q2 & D2 on

**Figure 1.8: Current Dynamics in a Switching Circuit**

When both switches $Q_1$ and $Q_2$ are turned on Fig. 1.8a, a constant voltage is applied to the excitation coil, and the current starts to increase. The energy is stored in the magnetic field and converted to mechanical energy [3]. When both switches are turned off Fig. 1.8b, the freewheeling diodes $D_1$ and $D_2$ allow the existing current in the coil to keep flowing in the same direction. However, the reverse voltage applied to the excitation coi1 forces the current to decrease. The unused energy in the magnetic field is sent back to the voltage supply as seen in the direction of the current. When only one switch $Q_2$ is turned on Fig. 1.8c, the stored energy is dissipated by the phase resistance and the back emf developed in the coil, and thus, the phase current slowly decreases. If the initial current is zero in Fig. 1.8c, then the current will remain zero because there is no voltage applied across the coil. The switches are turned on and off to control a desired current level for each phase.

## 1.5 RELATIONSHIP BETWEEN INDUCTANCE AND ROTOR POSITION

The torque characteristics are dependent on the relationship between flux linkages and rotor position as a function of current [10]. The inductance corresponds to that of a stator-phase coil of the switched reluctance motor neglecting the fringe effect and saturation. From Fig. 1.9a and b, the various angles are derived as:

$$\theta_1 = \frac{1}{2}\left[\frac{2\pi}{P_r} - (\beta_s + \beta_r)\right]$$

$$\theta_2 = \theta_1 + \beta_s$$

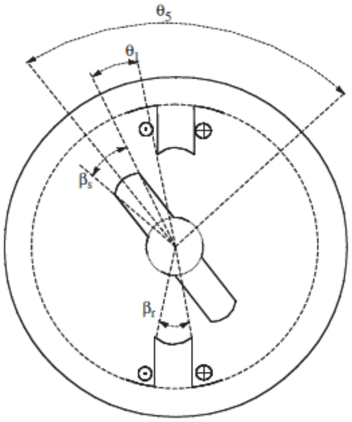
$$\theta_3 = \theta_2 + (\beta_r - \beta_s)$$

$$\theta_4 = \theta_3 + \beta_s$$

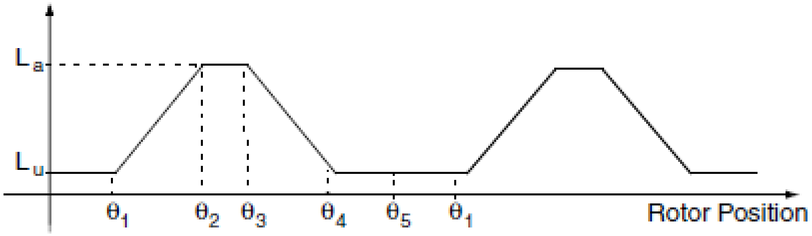
$$\theta_5 = \theta_4 + \theta_1 = \frac{2\pi}{P_r}$$

Where $\beta_s$ are $\beta_r$ stator and rotor pole arcs, respectively, and $P_r$ is the number of rotor poles. Four distinct inductance regions emerge:

- **$0 - \theta_1$ and $\theta_4$ -$\theta_5$:** The stator and rotor poles are not overlapping in this region and the flux is predominantly determined by the air path, thus making the inductance minimum and almost a constant. Hence, these regions do not contribute to torque production. The inductance in this region is known as unaligned inductance, $L_u$.
- **$\theta_1$– $\theta_2$:** Poles overlap, so the flux path is mainly through stator and rotor laminations. This increases the inductance with the rotor position, giving it a positive slope. A current impressed in the winding during this region produces a positive (i.e., motoring) torque. This region comes to an end when the overlap of poles is complete [10].



**(a)**



**(b)**

**Figure 1.9: Derivation of Inductance vs. Rotor Position from Rotor and Stator Pole Arcs for an unsaturated Switched Reluctance Machine. (a) Basic Rotor Position Definition in a Two Pole SRM. (b) Inductance Profile.**

- **$\theta_2$– $\theta_3$:** During this period, movement of rotor pole does not alter the complete overlap of the stator pole and does not change the dominant flux path. This has the effect of keeping the inductance maximum and constant, and this inductance is known as aligned inductance, $L_a$. As there is no change in the inductance in this region, torque generation is zero even when a current is present in this interval. In spite of this fact, it serves a useful function by providing time for the stator current to come to zero or lower levels when it is commutated, thus preventing negative torque generation for part of the time if the current has been decaying in the negative slope region of the inductance.
- **$\theta_3$– $\theta_4$:** The rotor pole is moving away from overlapping the stator pole in this region. This is very much similar to $\theta_1$– $\theta_2$ region, but it has decreasing inductance and increasing rotor position contributing to a negative slope of the inductance region [10]. The operation of the machine in this region results in negative torque (i.e., generation of electrical energy from mechanical input to the switched reluctance machine).

For rectangular currents, it can be seen that the motoring torque is produced for a short duration in pulsed form, resulting in a large torque ripple. This can create problems of increased audible noise, fatigue of the shaft, and possible speed oscillations. The torque ripples are minimized by designing the machine such that the inductance profiles of two succeeding phases overlap during the ending of one and the beginning of the other.

## 1.6 SRM CONFIGURATIONS

Switched reluctance motors can be classified as shown in Fig. 1.10. The initial classification is made on the basis of the nature of the motion (i.e., rotating or linear).

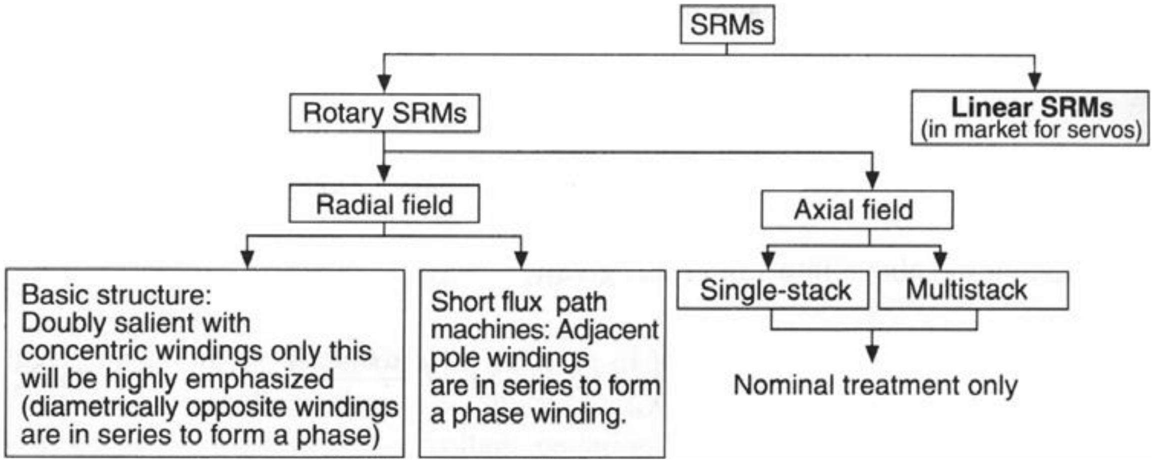


**Figure 1.10: Configuration of SRM**

### 1.6.1 ROTARY SRM

The rotary machine-based SRMs are further differentiated by the nature of the magnetic field path as to its direction with respect to the axial length of the machine. If the magnetic field path is perpendicular to the shaft, which may also be seen as along the radius of the cylindrical stator and rotor, the SRM is classified as radial field [10]. When the flux path is along the axial direction, the machine is called an axial field SRM.

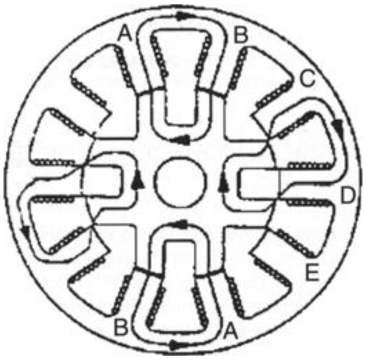


**Figure 1.11: Rotary Machine SRM**

Radial fields SRMs are most commonly used. They can be divided into shorter and longer flux paths based on how a phase coil is placed. The conventional one is the long flux path SRMs, in which the phase coil is placed in the diametrically opposite slots. In the shorter flux path SRMs, the phase coil is placed in the slots adjacent to each other, as shown in Fig. 1.11. Short flux path SRMs have the advantage of lower core losses due to the fact that the flux reversals do not occur in stator back iron in addition to having short flux paths. However, they have disadvantage of having a slightly higher mutual inductance and a possible higher uneven magnetic pull on the rotor.

### 1.6.2 AXIAL FIELD SRM

The axial configuration of a SRM is shown in Fig. 1.12. This type of SRMs is ideal for Applications where the total length may be constrained, such as in a ceiling fan or in a Propulsion application [5].

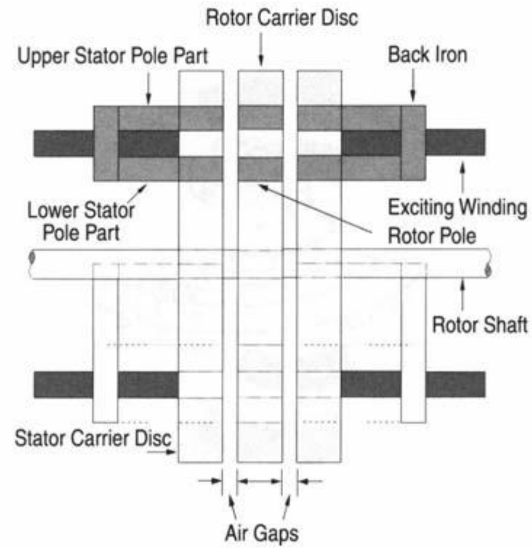


Figure 1.12: Axial Field Switched Reluctance Motor

The disadvantage of this configuration is that the stator laminations have to be folded one on top of the other, unlike the simple stacking of laminations in the radial field configuration. the advantage of lower core losses due to the fact that flux reversals do not occur in stator back iron in addition to having short flux paths. They have the disadvantages of having a slightly higher mutual inductance compared to conventional radial field SRMs and a possible higher uneven magnetic pull on the rotor. Conventional radial field SRMs with longer flux paths have been established for many applications due to overwhelming research and development data available on these machines. A recent variation of this type has full pitch coils [5]. A hybridized version of radial field SRMs with permanent magnets placed either in the back iron or on the stator poles, similar to pole shoes in configuration, has been studied and is known as a flux reversal machine. By bringing the permanent magnets onto the stator, the machines can have the high-speed and high-response operational advantages unique to the SRMs.

### 1.6.3 SINGLE-PHASE SRM

Single-phase SRMs are of interest as they bear a strong resemblance to single phase induction and universal machines and share their low-cost manufacture as well. High-speed applications are particularly appealing for single-phase SRMs [6]. When the stator and rotor poles are aligned, the current is turned off and the rotor keeps moving due to the stored kinetic energy. As the poles become unaligned, the stator winding again is energized, producing an electromagnetic torque . A problem with single-phase SRM operation arises only when the stator and rotor poles are in alignment at standstill or the rotor is at a position where the torque produced may be lower than the load torque at starting. This can be overcome by having a permanent magnet on the stator to pull the rotor away from the alignment, or to an appropriate position, to enable the generation of maximum electromagnetic torque, as shown in Fig. 1.13.

The single-phase SRMs operate with a maximum duty cycle of 0.5, and therefore, they have a torque discontinuity that results in torque ripple and noise [6]. Applications, which are insensitive to this drawback, such as hand tools and home appliances, are ideal for this machine.

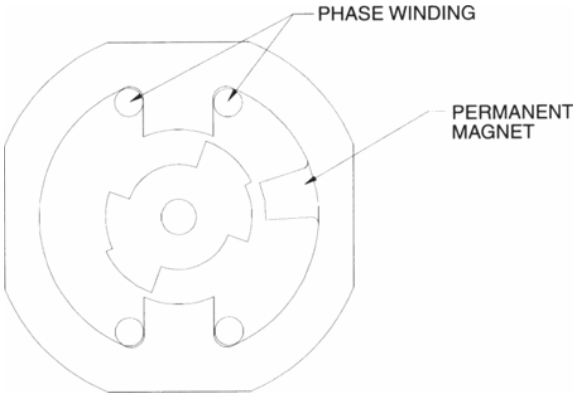


**Figure 1.13: Single-Phase SRM with Permanent Magnet to enable Starting**

Starting from any rotor can also be achieved by shifting one pole from its normal position by as much as 20°/$P_s$, where $P_s$ is the number of stator poles, by having two different gaps (steps) in the rotor poles for each half of the pole arc as shown in Fig. 1.14.

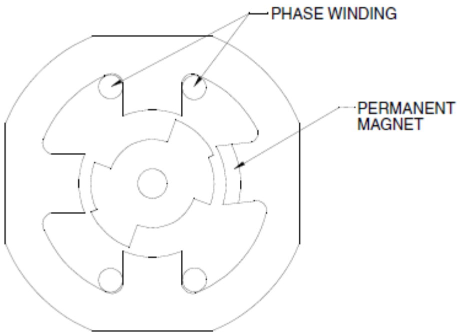


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**Figure 1.14: Single-Phase Machine with Shifted Pole Pair and Parking Magnet**

By shaping the stator poles with side shifts and pole horns, by shaping the stator and rotor pole, or by shaping the stator poles to provide graded air gaps. Single-phase motors have also been designed with a claw pole structure, with six poles on the stator and rotor having both radial and axial air gaps, offering higher efficiency than that of standard single-phase machines with only radial air gaps [6]. The construction of this machine is a little more intricate than its counterpart and may not be attractive for large-scale production. All of these methods provide asymmetric saturation in the stator and rotor, resulting in shifting of the flux axis and hence variation in the capability to provide electromagnetic torque at all positions.

### 1.6.4 LINEAR SRMs

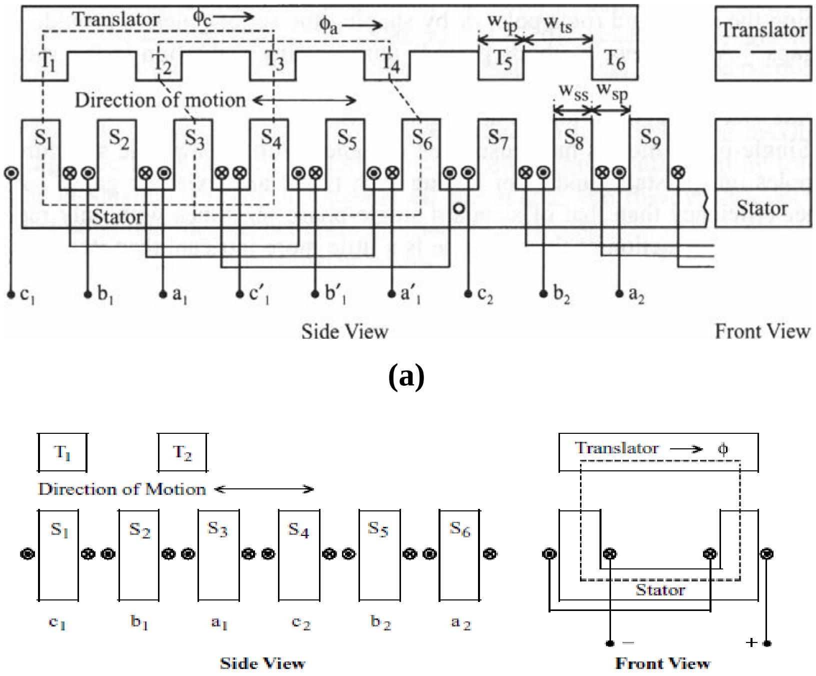
Linear motor drives are being increasingly considered for machine tool drives because they reduce the need for mechanical subsystems of gears and rotary-to-linear motion converters, such as lead screws [8]. Positioning accuracy is improved by the absence of gears that contribute to the backlashes in the linear motor drives.

Linear machine drives combined with electromagnetic levitation are strong candidates for conveyor applications in semiconductor fabrication plants and possibly in low- and high speed transit applications because of their ability to produce propulsion force on the rotating part, known as the translator, without mechanical contact and friction.

Linear switched reluctance machines (LSRMs) are the counterparts of the rotating switched reluctance machines. In fact, the linear switched reluctance machine is obtained from its rotary counterpart by cutting, along the shaft over its radius, both the stator and rotor and then rolling them out. In this section, various linear switched reluctance machine configurations are introduced. Further, the ideal inductance profile is related to the stator and translator lamination dimensions. A similar relationship for the rotary switched reluctance machine that has been derived earlier is worth noting.

### 1.6.4.1 MACHINE TOPOLOGY AND ELEMENTARY OPERATION OF LSRMs

A linear SRM may have windings either on the stator or translator (the moving part), whereas in the rotary switched reluctance machine the windings are always on the stator and the rotor contains no windings [7, 9]. Regardless of the location of phase windings, the fixed part is called either a stator or track and the moving part is called a translator.



(a)

(b)

**Figure 1.15: Three-Phase Linear SRMs with Longitudinal and Transverse Flux Paths (a) Three-Phase Longitudinal Linear SRM (b) Three-Phase Transverse Linear SRM**

There are two distinct configurations of linear SRM in the literature: longitudinal flux and transverse flux [9]. These two configurations can be obtained by unrolling both the stator and rotor of a rotary SRM with a radial magnetic flux path and axial magnetic flux path, respectively. Fig. 1.15 shows the longitudinal flux and transverse flux configurations for three-phase LSRM with an active (containing windings) stator and passive (with no windings) translator topology.

The longitudinal magnetic flux path configuration Fig. 1.15a is a linear counterpart of three-phase radial flux rotary SRM. The flux path in this machine is in the direction of the vehicle motion. This machine is simpler to manufacture, is mechanically robust, and has lower eddy current losses as the flux is in the same direction as the translator motion.

A transverse flux design Fig. 1.15b has the flux path perpendicular to the direction of vehicle motion. It allows a simple track consisting of individually mounted transverse bars. As the flux is perpendicular to the direction of motion, an emf is induced in the core, resulting in high eddy current losses [8, 9]. Longitudinal flux and transverse flux configurations for four-phase LSRM with an active translator and passive stator structure are shown in Fig. 1.16. The active stator and passive translator SRM configuration has the advantage of having the power supply and power converters being stationary, resulting in reduced weight of the vehicle.

This design, however, requires a large number of power converter sections along the track, resulting in high costs. On the other hand, a structure with an active translator and passive stator structure requires only one section of the power converter, but the power to the converter in the translator requires transfer by means of contact brushes which is not desirable for high-speed applications or by inductive transfer with additional power-converter circuits, with consequent complexity and higher costs.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 INTRODUCTION

Switched Reluctance (SR) machines are relatively new additions to a group of well-established variable-speed electrical machines. The major difference that distinguishes them from other conventional drives is simple, low cost, and rugged constructions. The simplicity of the mechanism is the result of their torque production principle, so called variable reluctance principle. SR machines produce torque without any permanent magnets and with no concentrated windings on their shaft. This unique torque production principle allows SR machines to have the benefits of reliability and capability of four-quadrant operation in a wide speed range. Other advantages of SR machines are also known to be the high torque-to-inertia ratios and high torque-to-power ratios. These attractive features have led SR machines to be potential candidates for applications in industrial and commercial markets. In this chapter literature of switched reluctance motor is reviewed. The converter topologies and soft switching converters for switched reluctance motor are reviewed.

Switched reluctance motors (SRM) and their drives for industrial applications are considered in many references to be of recent origin. Krishnan referred the first proposal of a variable reluctance motor for variable speed application to 1969, and the originality of the motor itself to 1842. Some other authors dated back the first acknowledged application of Switched Reluctance Motor to the late 1830s. Since that date, the Switched Reluctance Motor was proposed but with major drawbacks, which severely limited the applications of this motor in industry, these major drawbacks are:

- Necessity of electronic commutation.
- Complicated analysis due to non-linear characteristics.
- Difficulty of control.
- Need to shaft position sensor.
- Torque ripples.
- Acoustic noise

R. Krishnan, M. Abouzeid and X. Mang [11] presented a design procedure for axial field switched reluctance motors. Axial field configurations are attractive for applications where the overall length of the motor has to be short; the design procedure is based on the classical machine design equations applicable to all other machines. The effects of various diameters, number of turns per phase, axial length and pole arc on power output are quantified.

U.S. Deshpande, J.J. Cathey and E. Richter [12] presented a high force density linear switched reluctance machine. The linear switched reluctance machine (LSRM) lends itself to double-sided excitation and multiple translator (or "rotor ") configurations that can yield high force density designs suitable for controlled linear motion in hostile environments. This paper presents the particular design of a 6:4, double-sided, double-translator LSRM that develops 5.1 Lbs/in sq. of air gap force shear.

Byeong-Seok Lee, Han-Kyung Bae and Praveen Vijayraghavan [13] developed the standard design procedure for a single-sided and longitudinal flux-based linear switched reluctance machine. The proposed design procedure utilizes the rotating switched reluctance machine design by converting the specifications of the linear machine into the equivalent rotary machine. The machine design is carried out in the rotary domain, which is then transformed back into the linear domain.

Cheng-Tsung Liu and Yan-Nan Chen [14] provided a systematic guidance for linear switched reluctance machine design. By classifying the feasible polygons for desired machine operations, the physical size limits of either longitudinal or transverse flux linear machine poles or pole pitches can be determined. The classified feasible polygons for different linear SRMs and various dependent parameter selections have been devised and their suitability's have been demonstrated.

M. Ehsani, I. Husain, K. R. Ramani and J. H. Gallow [15] presented **a** modified converter topology for star connected switched reluctance motors suitable for low voltage applications. A dual time constant freewheeling circuit had been designed to improve the drive performance and efficiency over a wide range of speeds.

Do-Hyun Jang, Iqbal Hussain and Mehrdad Ehsani [16] described the efficiency and performance analysis of dual decay converter for star connected switched reluctance motor drives in low- voltage applications. In order to improve the efficiency and to maintain the control system simple, it is appropriate to turn off the freewheeling switch at about peak point of the inductance profile with a relatively high value of dump resistor.

Geun-Hie Rim, Won-Ho Kim, Eun-Soo Kim, Ki-Chul Lee [17] described a chopping-less converter for switched reluctance motor with unity power factor and sinusoidal input current. It consist of a pair of boost-buck power converters and a machine converter. The wide pre-voltage regulations by the two power conversion stages eliminate the high voltage-chopping to control the stator winding currents and also improved input current waveform.

R. Krishnan [18] introduced a novel converter topology for switched reluctance motor drives. The converter provides a full four quadrant operation with independent energization and commutation of each phase winding. It requires no snubbing for its phase switches and only a minimum set of power supplies.

Geun-Hie Rim, Won-Ho Kim and Jung-Goo Cho [19] described ZVT single pulse current converter for switched reluctance motor drives. By adding a ZVT-chopping switch in the front-end, all switches in the machine side converter can be operated without any chopping to regulate phase current. This allows the use of low cost and slow-switching devices for the machine side converter. ZVT technology contributes to enhance the system efficiency.

T.W. Ching, K.T. Chau and C.C. Chan [20] introduced a novel zero-voltage soft-switching converter for switched reluctance motor drives. The ZVT converter possesses the advantageous that all switches and diodes can achieve ZVS when voltage and current stresses are kept at unity. It is especially advantageous for SRM drives demanding efficient regenerative braking.

A. Consoli, A. Testa, **N.**Aiello, F. Gennaro, M. Lo Presti [21] presented an innovative converter topology based on C-dump converter configuration that is able to act as an active power factor controller. According to the features of the proposed circuit a conventional PFC stage is unnecessary to comply with European standards on power quality, thus reducing the cost and the complexity of switched reluctance motor drives aimed to equip home appliances.

Do-Hyun Jang [22] proposed the new converter topology using half bridge inverter for the switched reluctance motor drives. The converter maintains the high efficiency though switches are reduced and energy is returned to the source after the turn-off. But this converter applies only to even number of stator slots.

Tilak Gopalarathnam and Hamid A. Toliyat [23] proposed a high power factor converter topology with SEPIC front-end for switched reluctance motor drives with unipolar currents. The converter is designed to operate in the discontinuous conduction mode**.** The front-end converter performs the tasks of power factor correction as well as phase-defluxing.

M. Hiller, R. Marquardt [24] presented a new converter concept for SRM drives with multiple energy sources. An additional switched capacitor per motor phase results in an extended control flexibility. This results in significant improvements of maximum torque, efficiency or torque ripple up to maximum speed. Furthermore a second energy source can easily be integrated in the drive system.

P. Bazzaz, Ebrahim Afjei and Hamid A. Toliyat [25] developed and demonstrated a hybrid converter for high speed operation of switched reluctance motor drives. A capacitor is charged through the resonant circuit and discharge during next working stroke. It provides faster rate of rise and fall for the phase current, which permits the motor to operate at higher speeds.

R. Jeyabharatlil, P. Veena and M. Rajaram [26] introduced a new converter topology for switched reluctance motor drives .A sensor less circuit with SEPIC working as Power Factor Pre-regulator (PFP) is used which acts as both a power factor correction as well as phase-de fluxing component, reducing the device count, better current regulation.

Chen Hao and Ahn Jin-Woo [27] introduced the novel combined control strategy. The turn-on angle and the turn-off angle in the power converter at the different range of the rotor speed are presented. The output and the rotor speed of the drive are controlled over the low rotor speed range by regulating the duty ratio of the pulse width modulation signal. The novel combined control strategies have the advantages in the high systematical efficiency and the low current rating need of the main switches in the power converter.

Wanderlei Marinho da Silva and Clovis Goldemberg [28] presented the full bridge C-Dump converter with and without the equalization leg. Elimination of this equalization leg is very attractive since it will reduce semiconductor number and also eliminate the inductor, which have low-cost and a large volume production, to drive switched reluctance machines. These machines can be easily assembled since they require no special winding connections.

Yuen-Chung Kim, Yong-Ho Yoon, Byoung-Kuk Lee, Hack-Seong Kim and Chung-Yuen Won [29] proposed a new type of four-switch converter for switched reluctance motor to provide a possibility for realization of low cost three-phase switched reluctance motor drive system. A new proposed converter and control scheme is explained and the current control algorithm is designed and implemented to validity of the proposed converter is verified by simulation produce the desired dynamic performance.

H. Chen, Y.Zhu and D. Zhang [30] presented the topology of the power converter main circuit for a developed 600kw switched reluctance motor drive with the three-phase 12/8 structure reluctance motor. The asymmetric bridge circuit could be selected based on the comparison of the four topologies. The method could be suitable for low cost and the design of the power converter in the other high power switched reluctance motor drive.

Hong-Je Ryoo, Won-Ho Kim, Geun-Hie Rim, Wook Kang, Ji-Ho Park, Ghung-Yuen Won [31] proposed a new split source type converter topology by adding two switches and diodes to split source converter. The proposed converter has a good advantage of using double DC link voltage that enables to suppress the winding current quickly resulting in minimization of negative torque and has more efficiency and more power from the same motor in the high-speed operation.

M. Dahmane, F. Meibody-Tabar, F-M. Sargos [32] presented two DC voltage-boosting circuits which enhance the performance of three phase switched reluctance motors. The first one consists in a parallel capacitor-diode combination, in the second one; a parallel transistor is added to the former circuit. The boost circuit generates an additional voltage during the commutations, which increases the current derivative, so that a quasi square current waveform can be imposed even at high speeds.

S. Woothipatanapan, P. Chancharoensook and A. Jangwanitlert [33] presented a method to improve the efficiency of a standard asymmetric half-bridge converter for switched reluctance motor drives at low speed operation. The method provided a good mean for determining optimum snubber capacitor, so they can improve the efficiency of a standard converter for SRM drives and reduced the turn-off losses in the chopping switches of the converter.

Natália S. Gameiro and A. J. Marques Cardoso [34] presented a fault tolerant power converter applied to four-phase switched reluctance motor. The proposed converter is capable to secure the operation of all phases when a fault occurrence forces the disconnection of one of the power converter switches, without redundant power converter switches or diodes. Electromagnetic torque is clearly reduced as well as the electromagnetic torque ripple and speed oscillation.

Z. Nie and A. Emadi [35] presented the concept of integrated converters to reducing power electronic cost for switched reluctance motor drives. Basic converters based on the sub-integrated concept are used for the purpose of power factor correction. Basic converters for DC-SRM drives are proposed. Finally, according to the integrated converter concept, three integrated converters based on the variable DC link voltage for switched reluctance motor drive.

M. Krishnamurthy, B. Fahimi and C. S. Edrington [36] three various circuit topologies for operation of a bipolar switched reluctance motor drive have been introduced and explained.

The silicon losses in each circuit topology has been computed and compared with that from a conventional unipolar switched reluctance motor drive over a wide range of speed.

Yong-Ho Yoon, Dae-Hee Han, Se-loo Kim, Duck-Kyu Kim and Chung-Yuen Won [37] presented the current hysteresis control method to improve the operational performance of switched reluctance motor. This method maintains a generally flat current waveform. By using current hysteresis control method improved torque ripple problem as single pulse mode in low speed. Power loss of three switches reduced with ZVS and ZCS by series resonant circuit.

Sayeed Mir, Iqbal Husain and Malik E. Elbuluk [38] presented two energy-efficient converter topologies, derived from the conventional C-dump converter for switched reluctance motor drives. The converters are able to improve upon the limitations of the conventional C-dump converter, resulting in higher efficiency, lower cost and simpler control.

Wang Xiaoyuan, Pan Hao and Wang Chuan [39] introduced a new power converter circuit of switched reluctance motor based on two intelligent power modules. Half number of main switch devices in every intelligent power module is used; it avoids many problems facing in general power converter design like problem of matching freewheeling diodes, external driven and design of protection circuit.

K.Y. Cho and J.Y. Lim [40] proposed a power-converter circuit for a switched reluctance motor. It consists of one switching device per phase and a dump capacitor auxiliary switch and fly-back transformer. The energy of the off-going phase is returned to the DC-link capacitor through the transformer. The drive efficiency of the proposed converter is lower than that of the asymmetric converter.

L.Morel, H.Fayard, R. Vives Fos, A. Galindo and G Abba [41] presented a new rotor structure with a composite material increasing the motor features has been achieved, higher speed and mechanical power can be reached. The maximal speed is about 200.000 rpm with a power of 1kW on the mechanical shaft. The converter is controlled by a DSP card**.**

Feel-Soon Kang, Jung-Han Lee, Cheul-U Kim and Sung-Jun Park [42] presented a single-phase power factor corrected converter for switched reluctance motor drives. It combines a power factor corrected converter and a conventional asymmetric switched reluctance motor driver into one power stage, the configuration has a simple structure resulted in low cost.

S.J. Watkins, J. Corda and L. Zhang [43] presented a new family of multilevel asymmetric power converters which are suitable for unipolar current loads like switched reluctance motor drive. The additional control flexibility offered by the multilevel voltage modes of operation can help to improve system performance, especially at low speeds.

Jianing Liang, Seung-Hun Seok, Dong-Hee Lee and Jin-Woo Ahn [44] proposed a novel passive boost converter for three- phase SRM. A passive capacitor circuit is added in the front-end. The two capacitors can be connected in series and parallel, the double dc-link voltage can be obtained. Due to the high excitation and high demagnetization voltage, the output power of proposed converter is higher than conventional converter.

K.J. Tseng and J. Wang [45] proposed a single pulse operation switched reluctance motor converter topology based on the basic buck-fronted topology and the modified C-dump topology. The proposed power converter needs only (n+l) switches, supports single-pulse-operation, provides suppressing voltage of nearly $-V_{dc}$, and requires no additional control for regulating the dump capacitor voltage.

Luo Jianwu, Zhan Qionghua [46] presented a paper on novel soft-switching converter for switched reluctance motor and its analysis and design. In order to improve the performance of switched reluctance motor (SRM) drives, some advanced control strategies have been proposed, such as current or flux linkage profile control. The proposed converter operates with low switching losses and low EMI, because all power semiconductor devices are soft-switched. The proposed circuit is very effective to control the phase current.

L.G.B.Rolim, W.I.Suemitsu, E.H.Watanabe and R.Hanitsch [47] introduced the soft-switching converters in association with switched reluctance motors (SRM) potentially allows the fabrication of motor drives with increased power density and with better efficiency than other types of drive system. The proposed converter operates with high efficiency in a broad speed range, because all power semiconductor devices are soft-switched.

Levi P.B. de Oliveira, Edison R. da Silva, AntBnio M. N. Lima, and Cursino B. Jacobina [48] introduced two new soft-switched converters for operation with the DC link controlled configuration. One advantage of the proposed topologies is the reduced number of components when compared to other topologies and also an improvement is obtained in the torque shape.

Patrick C. K. Luk. Ken P. Jiniipim [49] a new switching scheme for the switched reluctance motor which results in superior torque and current control over existing schemes. The new tri-static chopping technique developed is very simple to implement, flexible in operation and effective in achieving optimized overall system performance. The new scheme however requires the hysteresis current gap to be set suitably to achieve superior output response.

Mohammad Reza Yousefi, Khalil Rahimi and Majid Pakdel [50] proposed a novel two-quadrant soft-switched converter; there are no switches available for current boosting because it uses diodes in current return path. The proposed converter shows excellent performance and potential for various industry applications, high frequency-high-voltage choppers.

## 2.2 OBJECTIVE OF THE THESIS

The objective of this thesis is to develop a novel soft switching converter for switched reluctance motor drive. The design has been tried out with and without soft switching connected to the switched reluctance motor to have a relative comparison. Simulink models are developed using MATLAB software and their waveforms are discussed. The proposed models seem satisfactory from the results obtained.

# CHAPTER 3

# SOFT SWITCHING CONVERTERS

In the early days of solid-state power electronics, thyristors were the only controllable power semiconductors available [51]. Because they cannot be turned-off from the gate terminal, many ingenious auxiliary circuits have been developed, to allow thyristors to be used in power converters that could not be naturally commutated by the load or by the line voltage. Many circuits for thyristors forced commutation could be regarded as soft-switched, because they use controlled LC oscillations in order to reduce the current through the thyristors to zero before it can be turned off. The development of self-commutated power semiconductor switches with gate turn-off capability has led to the obsolescence of forced commutation, initiating the age of hard-switched converters.

Further development of power semiconductor technology has allowed the fabrication of faster and more rugged power semiconductor switches, leading to an enhancement in switching frequency and power level of converters.

However, the higher power and switching speeds of the switches have caused an increase of switching stresses on the power semiconductor switches. The fast switching transitions at higher voltage and current levels excites the parasitic inductances and capacitances close to the converter switches, giving rise to excessive voltages, currents and power losses during the switching process.

These switching stresses must be maintained under acceptable levels in order to keep the switching trajectory inside of the device's safe operating area (switching SOA) and therewith avoiding premature device failure. This can be accomplished by adding small inductances and capacitances to the circuit at the switch terminals, in order to slow down the rate of change of current and voltage on the switch, during the switching transitions. In this process, the small electromagnetic energy storage elements added to the circuit will trap some energy at each switching transition, and they must be reset at every cycle.

The trapped switching energy can be dissipated in a resistor (as in a dissipative snubber circuit), recovered to the source (regenerative snubbing), or it can be returned to the main circuit, as is done in resonant converters.

These methods of achieving switching stress alleviation can be thought of as a continuous evolution in type of response, as represented in Fig. 3.1 [51].

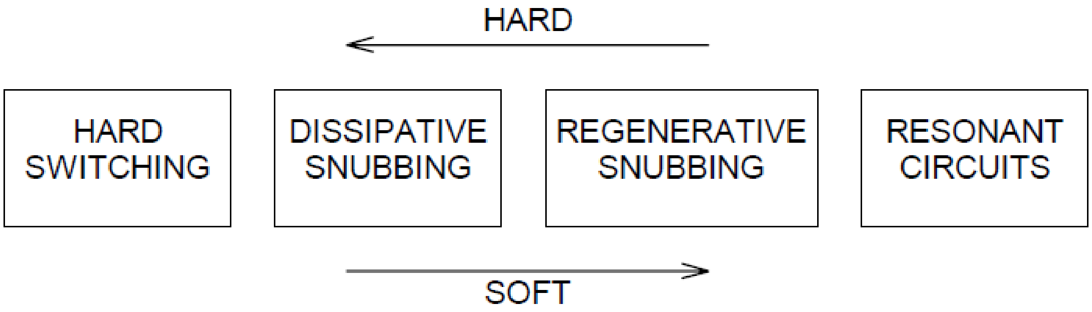


**Figure 3.1: From Hard to Soft Switching**

## 3.1 CLASSIFICATION OF SOFT-SWITCHING CONVERTERS

The term soft-switching is very broad and can be globally used to designate many different concepts and topologies. Classification of soft-switched converters is not uniform among distinct authors. Many authors prefer the general designation "resonant converters", but it sometimes leads to misunderstandings [53]. Many soft-switching converters are not truly resonant. In several topologies, resonance (in fact only part of a free LC oscillation) is limited to the switching transitions, which has led to the terminology "resonant transition converters". In other soft-switching converters, the link voltage or the link current is turned to zero during short periods of time, creating opportunities for the main switches to be turned on or off. Previously, soft-switching converters used to be classified as resonant and quasi-resonant only. As soft-switching technology evolved, many new topologies were proposed, which did not fully complied with those categories. The following classification of soft-switching converters is proposed

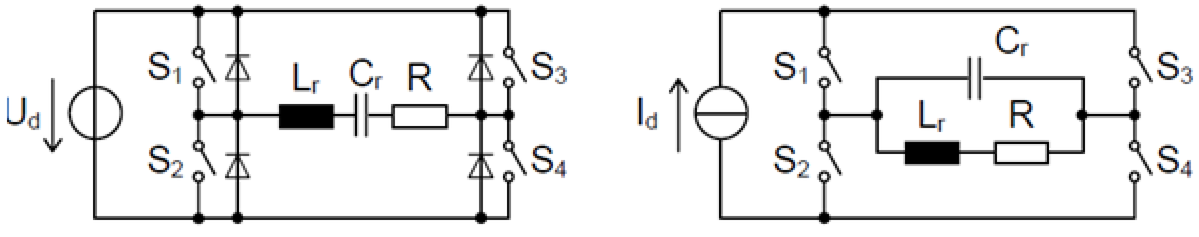
- Load-resonant converters
    - Voltage-source series-resonant converters:
        - Series-loaded resonant (SLR) converters;
        - Parallel-loaded resonant (PLR) converters;
        - Hybrid-resonant converters.

  - − Current-source parallel-resonant converters;
  - − Class E and subclass E resonant converters.
- Resonant-Switch converters
  - − Resonant-switch DC-DC converters:
    - Zero-current-switching (ZCS) converters;
    - Zero-voltage-switching (ZVS) converters.
  - − Zero-voltage-switching, clamped-voltage (ZVS-CV) converters, which are also referred to as pseudo-resonant converters and resonant- transition converters.

The main characteristics of each of the above related soft-switching converter families is briefly described in the following sub-sections.

### 3.1.1 LOAD-RESONANT CONVERTERS

For operation with load-resonant converters, an inductive load must be transformed in an LC resonant tank by adding capacitance and maybe also some additional inductance to the circuit [53]. The resonant tank is excited by rectangular pulses of voltage, as in a series-resonant converter, or current, as in a parallel resonant converter. These pulses are supplied from a converter that is topologically identical to a hard-switching converter, in the sense that no additional LC elements are connected directly to the switches, as shown in Fig. 3.2. Soft-switching operation is achieved just by turning the switches on and off at the right instants. Taking the case of the series-resonant converter as an example (Fig. 3.2 (a)), if a positive voltage step is applied to the load by closing switches $S_1$ and $S_4$ , the load current undergoes a free oscillation. As the current inverts, the corresponding anti-parallel diodes will conduct and the switches $S_1$ and $S_4$ can be opened without switching losses. Switches $S_2$ and $S_3$ can now be closed, inverting the voltage applied to the load and forcing its current to oscillate continuously, in a sustained resonance. The power flow to the load is controlled by the resonant tank impedance, which in turn depends on the switching frequency. This type of circuit is not very suitable for use with dynamic loads like electrical machines, in particular with SRMs, which exhibit inductances that change with position and current in a wide range, in a highly nonlinear manner. The main application field for this type of converter is induction heating.

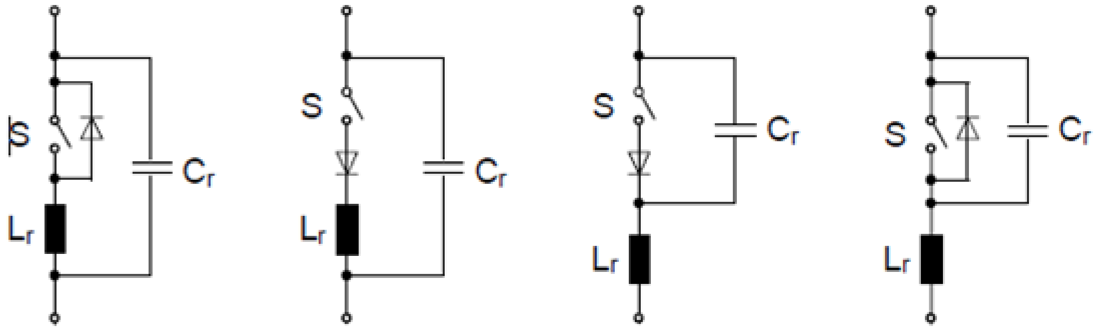


(a) (b)

**Figure 3.2: Series Resonant (a) and Parallel Resonant (b) Converters**

### 3.1.2 RESONANT-SWITCH CONVERTERS

A resonant switch is obtained by connecting resonant LC elements to a power semiconductor switch [52]. Some basic resonant switch configurations are shown in Fig. 3.3, but an extensive analysis of many circuit families of this kind can be found. The operating mode of a resonant-switch converter depends on the placement of the LC elements with respect to the power semiconductor element.



(a) (b) (c) (d)

**Figure 3.3: Resonant-Switch Configurations:**
**(a) Full-Wave ZCS (Zero-Current Switch);**
**(b) Half-Wave ZCS (Zero-Current Switch);**
**(c) Full-Wave ZVS (Zero-Voltage Switch);**
**(d) Half-Wave ZVS (Zero-Voltage Switch).**

For zero-current switching (ZCS) operation, the resonant inductor is directly connected in series with the semiconductor switch, as shown in Fig. 3.3 (a) and (b). The rate of rise of the current through the semiconductor switch is limited by the resonant inductor at turn-on. Additionally, the semiconductor switch can only be turned off when its current returns to zero and this is provided by the free oscillation of the resonant tank. In the circuit of Fig. 3.3 (a), the current in the resonant inductor is allowed to flow in the reverse direction, yielding operation in the so-called full-wave mode. Conversely, the resonant inductor current is not allowed to reverse in the circuit of Fig. 3.3 (b), which operates in the half-wave mode. The ZVS resonant-switch configurations shown in Fig. 3.3 (c) and (d) are dual to the above described zero-current resonant switches. The presence of a resonant capacitor in parallel to the power semiconductor elements in these circuits obliges that they are turned on only when the voltage across the capacitor is zero. The full-wave ZVS switch shown in Fig. 3.3 (c) allows a negative excursion of the resonant capacitor voltage, but in the half wave ZVS resonant-switch circuit of Fig. 3.3 (c), the capacitor voltage cannot undergo a negative oscillation [52]. The control of the output power in resonant switch converters is usually realized by use of frequency modulation. Some modifications in the resonant-switch circuits allow the use of pulse-width modulated control. This type of converter, however, has limited applicability in medium- to high-power electric motor drive systems, due to the higher current stress and associated conduction losses in the resonant switch in ZCS mode, as well as the higher voltage stress in ZVS mode. The main application area for this kind of converter is the field of switch-mode power supplies.

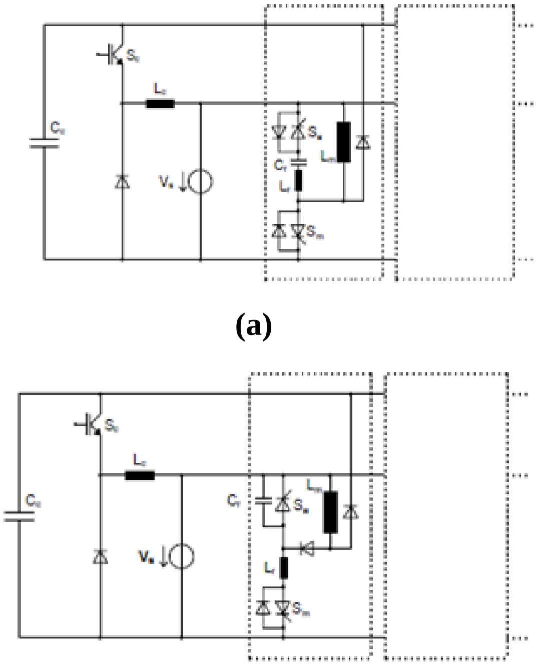
## 3.2 SOFT-SWITCHING CONVERTERS FOR SR DRIVES

The use of soft-switching converters in AC machine drive systems has been already well documented in the literature, with many works having been published. On the other hand, just a few reported applications of soft-switching techniques in SR drive systems are found in the literature. In the following sub-sections, the soft-switching SR converter topologies reported in the literature are discussed.

### 3.2.1 ZCS C-DUMP CONVERTER

There are two very similar soft-switching SR converter topologies. Schematic diagrams for these circuits are shown in Fig. 3.4 (a) and (b), respectively. Both circuits consist of a modified C-dump converter, comprising fast thyristors as main switches [55]. In both diagrams, the winding of one motor phase is represented by the inductor $L_m$. Auxiliary circuits including a resonant tank (formed by $L_r$ and $C_r$) and an auxiliary switch ($S_a$) have been added for each phase, in order to achieve zero current commutation of the main thyristor switches ($S_m$). However, the control of the voltage across the C-dump capacitor ($C_c$) is done by a hard-switched chopper in both circuits. This chopper comprises an inductor ($L_c$) and a semiconductor switch ($S_c$), which has been implemented with a bipolar transistor in and with an IGBT [58].

In the circuit (b), the main thyristors are operated as full-wave zero-current switches. The auxiliary thyristors provide free-wheeling paths for the phase current, allowing operation in soft-chopping mode. Phase current control is achieved through frequency modulation. In the circuit (a), the resonant oscillation is interrupted a half-cycle after turn-on of the main switch, and the full DC supply voltage can then be continuously applied to the phase winding for a controllable time. At the end of this period, the other half-cycle of the resonant transition is released by gating the auxiliary thyristors, in order to turn off the main switch at zero current. This control method allows the use of PWM to regulate the phase currents. However, soft-chopping is not possible in this circuit. Additionally, the direct connection of the main thyristors to the C-dump diodes makes the turn-on behavior of the main switches to be dictated by the reverse recovery characteristics of the C-dump diodes, resulting in no alleviation of turn-on losses. In fact, both circuits are more likely to be classified as force-commutated thyristor converters than as actual soft-switching topologies. The high number of components is the major disadvantage of these circuits.



**(a)**

**(b)**

**Figure 3.4: ZCS C-dump converters**

### 3.2.2 SERIES-RESONANT SR CONVERTER

Resonant converter for SR drives, also using zero-current commutated thyristors as main switches [57]. A schematic diagram of this converter is shown in Fig. 3.5, for a 6/4 SR motor, having a three-phase power supply input. In this topology, the average voltage across the resonant capacitors $C_r$, i.e. the voltage applied to the phase windings is controlled by the repetition rate of the resonant current pulses injected in each phase circuit. The phase currents, in turn, are regulated in a CRPWM fashion, by making the average voltage applied to the phase windings to jump back and forth between a positive and a negative value, in a kind of indirect bang-bang control. No free-wheeling path is provided for the phase currents, so the current control can be regarded as hard-chopped.

For the voltage control of a phase to work properly during the dwell period, the voltage across the respective resonant capacitor $C_r$ must always be lower than the mean supply voltage at the beginning of each resonant cycle. This voltage difference $\Delta V$ is necessary to drive the resonant oscillation. Since the thyristor switches are connected as half-wave zero-current switches, each resonant current pulse will end after the first positive half-cycle. During one resonant pulse, the voltage across $C_r$, i.e. the phase voltage, rises from $V_s - \Delta V$ to $V_s + \Delta V$. At the end of each resonant pulse, the thyristors turn off under zero current and the phase voltage must be brought back to $V_s - \Delta V$. In this circuit, the motor phase current alone is relied upon to accomplish this task. As the motor phase inductances are much higher than the inductance of the resonant tank, the phase currents do not change significantly during one resonant cycle and can be regarded as constant. Therefore, the phase voltage will decay from $V_s + \Delta V$ to $V_s - \Delta V$ with a nearly constant slope, which will be proportional to the load current. The duration of this decay will also vary accordingly, and a new resonant pulse is triggered only at the end of this decay period [57].

As a result, the switching frequency will be strongly coupled to the load current. For operation with dwell overlap, the voltage across the off going phase must be regulated at $-V_s$, while the voltage across the ongoing phase must jump between $-V_s$ and $+V_s$ in order to control the phase current. This requires an interleaving or time-multiplexing of both control loops, and it may be difficult to achieve when the switching frequencies in the two phases are different, due to different current levels. As a result, the turn-off of a phase is strongly coupled to the turn-on of the next phase. In this circuit, the peak voltage stresses can be limited by choosing an appropriate value for $\Delta V$. The peak current stresses are also directly proportional to $\Delta V$ and inversely proportional to the characteristic impedance of the resonant tank $Z_r = L_r / C_r$. The reduced number of switches seems to be the main advantage of this circuit, but they must be rated to more than twice the supply voltage, so the cost savings are low. Furthermore, the control method employed for this converter is very complex and it is expected to exhibit a slower dynamic performance than a directly voltage-fed CRPWM control.

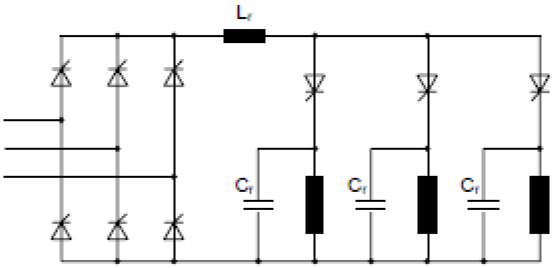


**Figure 3.5: Series-Resonant Converter for 6/4 SRM, with Three-Phase input.**

### 3.2.3 ZERO-VOLTAGE TRANSITION (ZVT) PWM SR CONVERTER

Single chopping switch is used to regulate the DC link voltage of a "Pollock" converter, using true PWM voltage control [56]. The chopping switch (S) is commutated at zero voltage with help from a sub-circuit comprising a resonant tank ($L_r$ and $C_r$) and an auxiliary switch ($S_a$), as shown in Fig. 3.6. However, the auxiliary switch itself is hard-switched. The authors propose the use of a power MOSFET as auxiliary switch, because of its low switching losses. The conduction losses in the resonant sub-circuit are also kept low, because it is only activated for a short time, preceding the turn-on of the chopping switch.

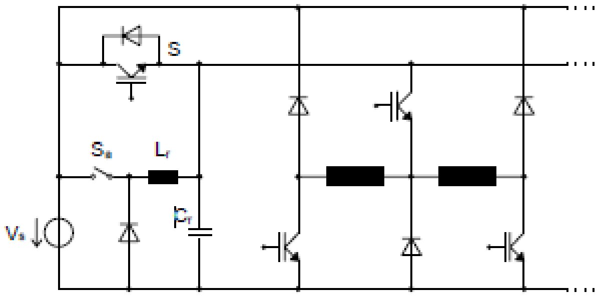


**Figure 3.6: ZVT PWM SR Converter**

When $S_a$ is turned on, assuming that $C_r$ is initially discharged, the DC link voltage will rise, describing a resonant oscillation. The voltage would ideally overshoot the supply voltage by 100%, but the anti-parallel diode of switch S will clamp the DC voltage at the supply level Vs.

Switch S can then be turned on under zero voltage, with low switching losses. After turn-on of S, switch $S_a$ is turned off in hard-switching mode [56]. When S is turned off, the resonant capacitor $C_r$ will provide ZVS conditions, slowing down the fall of the DC link voltage. This fall time, however, will depend strongly on the motor phase currents. The use of voltage PWM to control the motor speed does not allow the achievement of the best attainable dynamic response. If the control is modified, this circuit is capable of realizing current-regulated PWM. However, the current overlap capability will be limited if the current control is realized through the switch S only. Independent current control can be realized if switch S is used only to resonate the DC link voltage to zero, in order to create a zero voltage switching opportunity for commutation of the main output switches. As switch S must conduct the whole motor current, the conduction losses are expected to be up to ca. 30% higher, for operation in single-pulse mode.

### 3.2.4 AQRDCL SR CONVERTER

The application of an auxiliary quasi-resonant DC link (AQRDCL) to a SR machine drive is proposed [54]. A schematic diagram of the proposed circuit is shown in Fig. 3.7. In this topology, the switch $S_c$ is kept closed most of the time, connecting the supply voltage $V_s$ to the upper rail of the output section. When the main output switches have to be commutated, a resonant transition is started by triggering the auxiliary zero-current switch $S_a$ into conduction, in order to pre-charge the resonant inductor $L_r$. Switch Sa is kept closed until the energy is stored in $L_r$ is enough to ensure a full swing of the DC link voltage from Vs to zero. Switch Sc is then turned off under ZVS conditions, and the DC link voltage falls to zero with the wave shape dictated by the resonant tank formed by $L_r$ and $C_r$. When the DC link voltage passes through zero, the switch $S_s$ is closed, shorting the DC bus and holding its voltage at zero for a brief period, during which the main output switches can be commutated with low switching losses. The duration of this shorting period should be enough for the current in $L_r$ to reverse and to reach a magnitude that will guarantee the full swing of the DC link voltage back to $V_s$ when the switch $S_s$ is turned off. $S_s$ is switched off under ZVS conditions, and the energy stored in $L_r$ will give rise to the resonant oscillation with $C_r$, that will bring the DC link voltage back to the supply level $V_s$. In the circuit of Fig. 3.7, switch $S_a$ must be bi-directional in voltage and current. Furthermore, switch $S_c$ conducts the whole motor current, producing additional conduction losses. If the circuit is operated with tail current overlap, the voltage applied to an off-going phase during demagnetization will be reduced, because of the DC link resonance required for PWM current control of the next ongoing phase [54]. This shortcoming can be avoided if the upper diodes of the asymmetric half-bridge at the output section are connected directly to the supply rail instead of being connected to the quasi-resonant DC link.

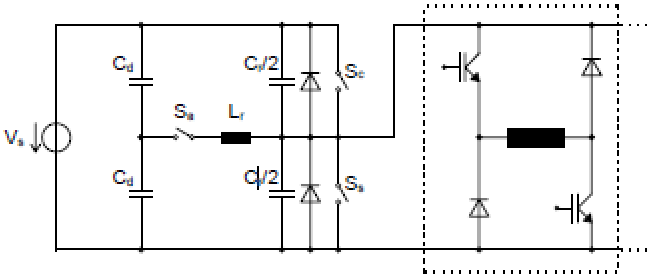


**Figure 3.7: AQRDCL SR Converter**

### 3.2.5 OTHER TOPOLOGIES

Some of those circuits would not suit very well to a high power density medium-power SR drive system. The most suitable converters for SR drives are current-regulated voltage-source converters, because they permit operation at wide speed ranges. Therefore, SRDCL converters are also not appropriate, due to their current-source behavior. Although the actively-clamped resonant DC link (ACRDCL) converter has been frequently pointed out as the most promising resonant converter topology for medium-power AC drive systems, no other author has published any work on attempting to adapt an ACRDCL converter for application in SR drive systems. Nevertheless, the ACRDCL seems to be a well-suited soft-switching circuit for high power density SR drives, because it has a low number of additional components and the voltage stresses are limited, according to the clamp factor. A possible implementation of ACRDCL SR converter is shown in Fig. 3.8.

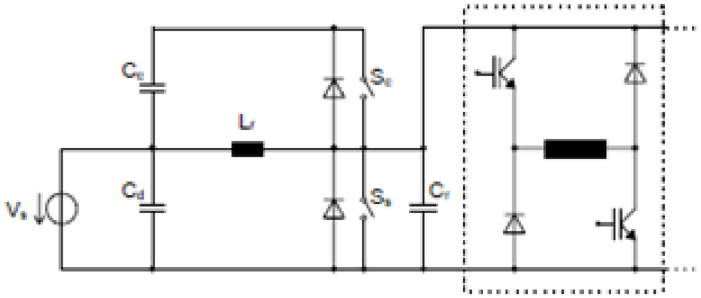


**Figure 3.8: A Possible Implementation of ACRDCL SR Converter**

## 3.3 TECHNOLOGICAL ASPECTS

### 3.3.1 POWER SEMICONDUCTORS

The constant evolution of power semiconductor device technology is causing a progressive overlap of application areas for different devices. Devices with ever higher voltage and current ratings are being developed every year and this affects the choice of the most appropriate power semiconductor switches for new designs. For electric drive applications, following controllable devices are presently commercially available:

**SCR:-** (Silicon Controlled Rectifier or Thyristor) - for very high power applications (>5 MW). Very high voltage blocking (>5 kV) and current conduction (>3 kA) capabilities. Has low switching speed and cannot be turned off from its control terminal (gate).

**GTO** (Gate Turn off Thyristor) - For high power applications up to some MW. Voltage and current ratings comparable to SCRs. Switching speed is not very high, but depending on the power level it can switch, in hard commutation, at frequencies up to few kHz. There are publications showing that GTOs can switch at frequencies up to 20 kHz if zero current switching is used. GTOs can be turned off from the gate, but the control current is relatively high and this is one drawback for low to medium power applications.

**BJT** (Bipolar Junction Transistor) - although many drive systems using these devices are still in operation, power bipolar transistors and power darling tons are being gradually replaced by MOSFETs and IGBTs in new designs. Relatively high turn-off losses and turn-off delay, second breakdown and non-negligible power consumption at the control terminal are major disadvantages of this kind of device in comparison with its competitors.

**MOSFET** (Metal-Oxide-Semiconductor Field Effect Transistor) - for low to medium power applications up to some kW [52]. However, high blocking voltage and high current conduction capabilities cannot be attained simultaneously. Low-current devices with voltage ratings up to 1 kV or low-voltage devices with current ratings up to some hundred amperes are commercially available.

**IGBT** (Insulated Gate Bipolar Transistor) - for medium power applications (<1 MW). By the time of writing of this work, IGBT modules with voltage blocking capabilities up to 3300V and current ratings up to ca. 1 kA have become commercially available.

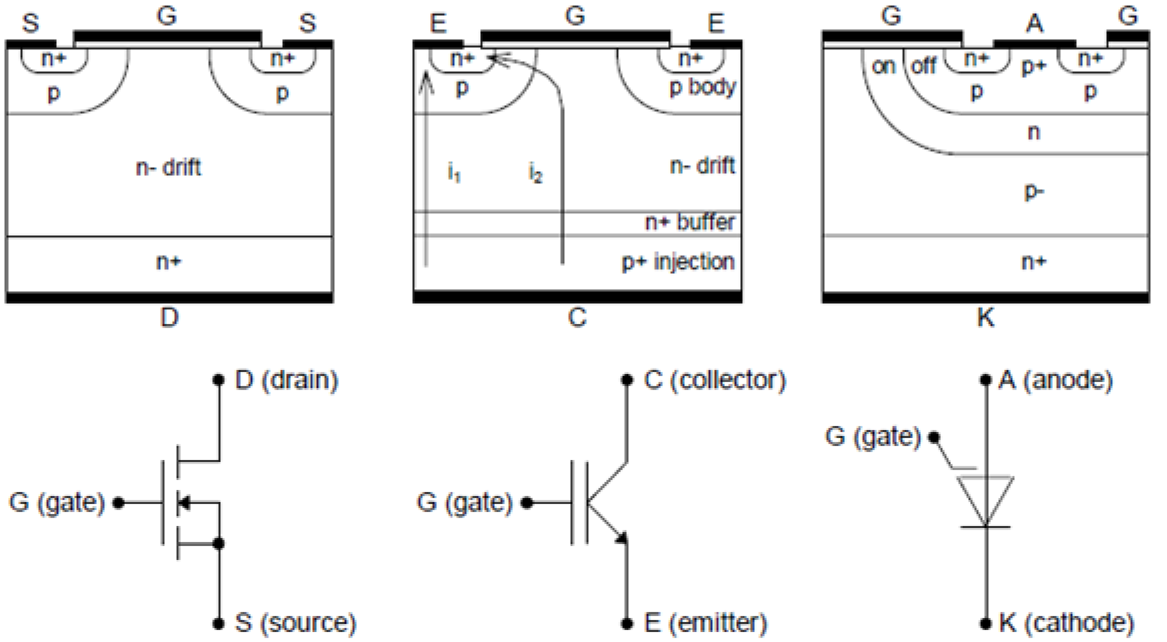
**MCT** (MOS-Controlled Thyristor) - an emerging device. Current and voltage ratings of MCTs comparable to those of IGBTs are technically possible, but currently available devices have voltage ratings up to 1 kV and current ratings less than 100 A.

### 3.3.2 MOSFET

The power MOSFET is a so-called unipolar device, because only majority carriers take part in the conduction process [52]. As a result, it exhibits a resistive behavior in the on-state. If the doping level is increased and/or the thickness of the drain drift zone (Fig. 3.9(a)) is decreased in order to achieve a lower on state resistance, then the voltage blocking capability is reduced and vice-versa. For devices with voltage blocking capability above a few hundred volts, the dependence of on-state resistance on breakdown voltage is approximately given by

$$R_{on} \propto V_{BR}^{2.5-2.7}$$

The practical consequence of this fact is the limitation of the current-carrying capability due to on-state power losses in devices with higher voltage ratings. Another important property related to the unipolar structure of the MOSFET is the very high switching speed. As there is no injection of minority carriers in the drift layer during conduction, there is neither delay nor tail current associated with removal of excess carriers at turn-off. The turn-on process is also very fast, mainly governed by the movement of charge carriers in the depletion layer and in the gate-source stray capacitances. Consequently, switching frequencies up to some hundred kHz can be easily reached in hard-switching mode. If soft-switching is used, the switching frequency can be increased up to some MHz However, due to the trade-off between current and voltage ratings mentioned above, the use of MOSFETs in electric motor drives is limited to low-voltage and low-power ranges.



(a) n-channel power MOSFET (b) n-type PT IGBT (c) p-type MCT

**Figure 3.9: Vertical Cross-Section of Power Semiconductor Devices.**

### 3.3.3 IGBT

There are basically two types of IGBT, termed punch-through (PT) and non punch- through (NPT). The main difference between the two types is the presence of a highly doped n+ buffer layer in the PT IGBT vertical structure, as shown in Fig. 3.9(b). The purpose of this buffer region is to limit the extent of the depletion layer for blocking voltages higher than a fraction of the device's breakdown voltage [53]. This allows for reduction of the drift region thickness, with attendant reduction of conduction losses. This buffer layer is not present in the NPT IGBT structure, which must therefore have a wider drift region to achieve the same voltage rating. Since this drift region is only lightly doped (low conductivity), conduction losses are expected to be higher than for the PT geometry. The switching behavior of the IGBT is also influenced by the type of structure. Although the switching mechanisms are basically the same in both structure types, differences in emitter efficiencies and in carrier lifetimes give rise to different magnitudes and durations of the so-called tail current at turn off. The emitter efficiency influences directly the portioning of the total device current in the two components i1 and i2 shown in Fig. 3.9(b).

Component i1 is a BJT-like current, and its path can be viewed as a p-n-p bipolar transistor. This component is primarily responsible for the turn-off current tail. Component i2 is a MOSFET-like current and thus drops very quickly at turn-off. The i1 component, however, continues to flow as a current tail, until the excess minority carriers recombine in the drift region. In NPT IGBTs, which usually exhibit lower emitter efficiency, i2 makes up most of the total device current (up to 90%).

Hence, the current fall-time at turn-off is commonly lower for NPT IGBTs. In NPT structures, the carrier lifetime in the drift region is kept high in order to minimize conduction losses, but this also implies a lower recombination rate and a slower decay of the tail current. On the other hand, PT IGBTs have higher emitter efficiencies, leading to higher initial values of current tail. However, the n+ buffer layer is designed to have a much shorter carrier life time than the drift region, causing a faster decay of the tail current. The overall effect of the switching mechanisms described above is a lower turn-off power loss for NPT IGBTs under hard-switching conditions. Nevertheless, this may be not true for soft-switching applications. Due to the longer current tail times exhibited by NPT IGBTs, they produce higher turn-off losses under zero-voltage soft-switching conditions than PT IGBTs. The current turn-off process of NPT IGBTs seems not to work properly at reduced rates of change of collector-to-emitter voltage during turn-off as it occurs in ZVS circuits. Switching losses even higher than in the hard-switched case have been reported for NPT devices in a ZVS application. In ZCS circuits, the turnoff behavior of NPT IGBTs is not a problem, because the circuit itself provides for current zeroing before the power semiconductor device is switched off. In contrast to this, PT IGBTs are better suited for zero-voltage soft-switching operation, but the rate of reduction of switching losses depends strongly on the dv/dt at turn-off. Additionally, the maximum attainable switching frequency depends on the type of device optimization, discussed next. In PT IGBTs, it is possible to modify the carrier lifetimes and the emitter efficiency of the BJT section, leading to different combinations of conduction and switching properties. Therefore, in PT IBGT chip design, a fundamental trade off exists between switching speed (and switching energy) and on-state voltage drop, i.e., between switching losses and conduction losses. A typical graph of achievable on-state voltage versus total switching energy for a second generation 600V IGBT is shown in Fig. 3.10. Most manufacturers have developed basically two types of second-generation. IGBT devices, one optimized for lower on-state voltage drop and consequently lower conduction losses, and another optimized for faster switching speed and lower switching losses. These families have been usually called "low saturation" and "fast switching" respectively. However, further optimization of IGBT chip properties has led to third-generation devices, which exhibit equal or lower conduction losses than second-generation low saturation devices and equal or lower switching losses than second-generation fast switching devices.

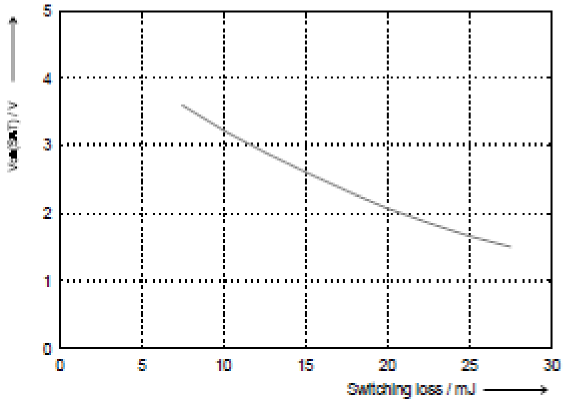


**Figure 3.10: Typical VCE (on) versus Switching Energy Relationship for a 600V IGBT at 1A/sq. mm.**

# CHAPTER 4

# RESULTS AND DISCUSSIONS

## 4.1 CONVERTER MODEL USING MOSFET

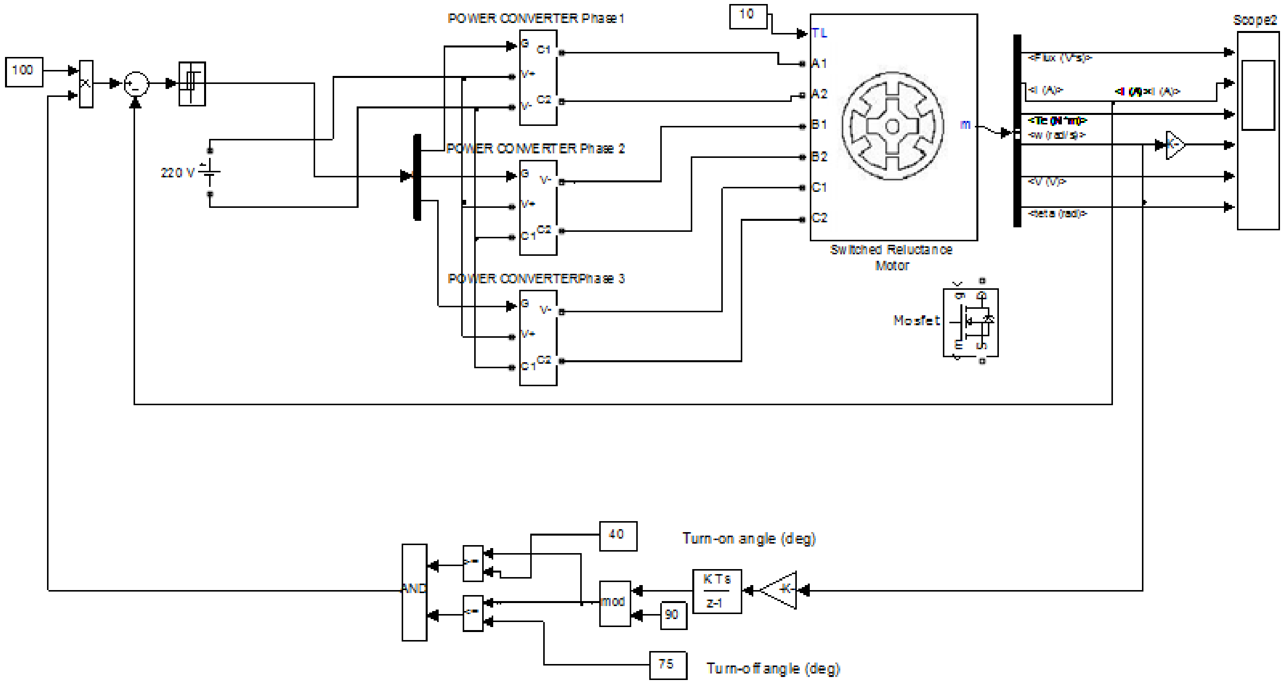


Figure 4.1: Switched Reluctance Motor with Power Converter Using MOSFET

As the power MOSFET is a so-called unipolar device, because only majority carriers take part in the conduction process. As a result, it exhibits a resistive behavior in the on-state. If the doping level is increased and/or the thickness of the drain drift zone is decreased in order to achieve a lower on-state resistance, then the voltage blocking capability is reduced and vice-versa. The practical consequence of this fact is the limitation of the current-carrying capability due to on-state power losses in devices with higher voltage ratings.

DC Converter here is primarily responsible for the turn-off current tail. Component i2 is a MOSFET-like current and thus drops very quickly at turn-off. The i1 component, however, continues to flow as a current tail, until the excess minority carriers recombine in the drift region.

## 4.2 SOFT SWITCHING CONVERTER MODEL USNG IGBT

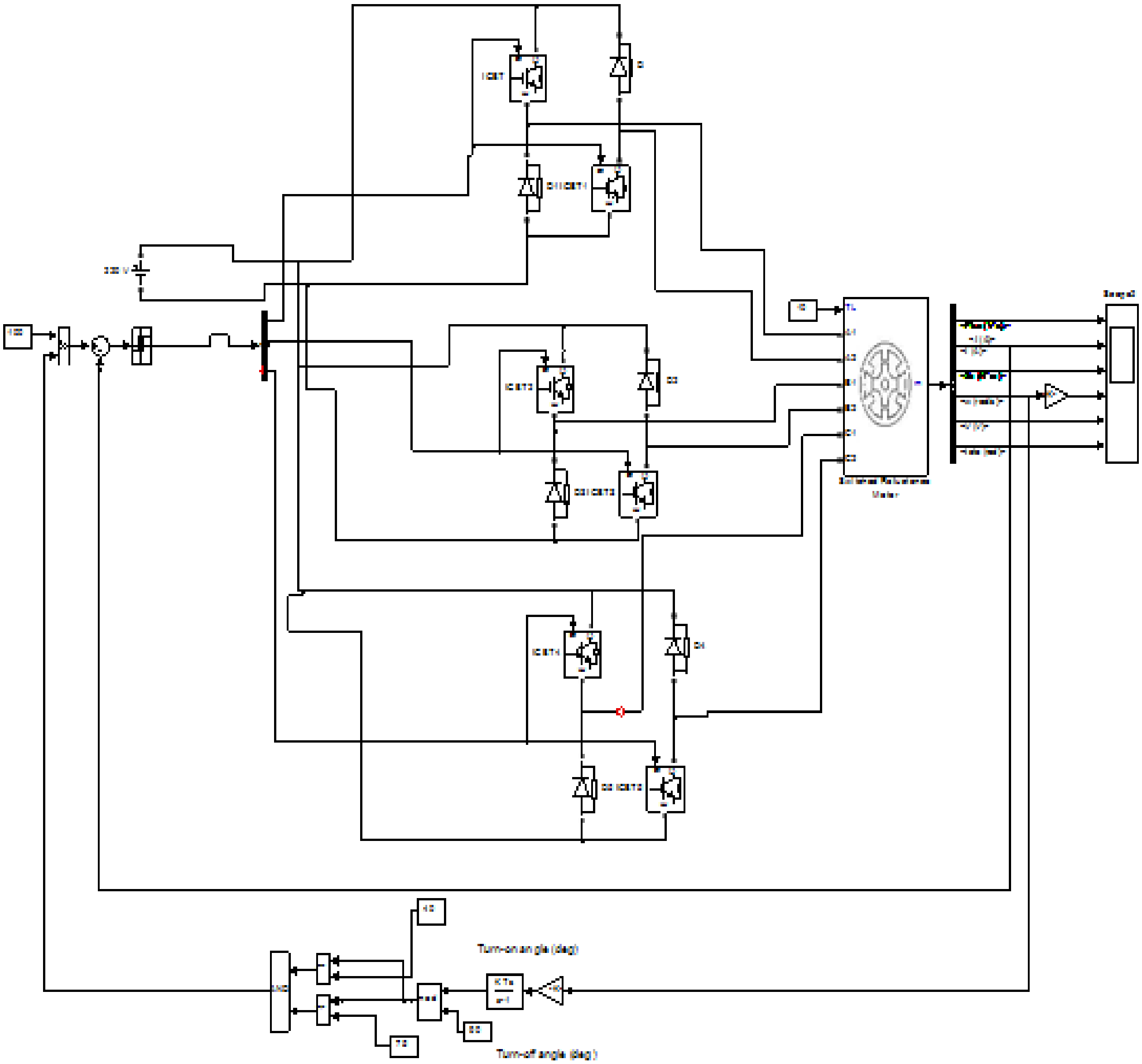


**Figure 4.2: Switched Reluctance Motor Converter Using IGBT**

The Soft switching circuit uses 6 IGBT’s .The IGBTs act as switches to provide a series of DC pulses to the Switched Reluctance Motor. Since SRM frequency controls are for 3-phase motors, there are six IGBTs, two for each phase. One IGBT connects each motor terminal to the positive side of the DC supplies (220 V) and one connects each motor terminal to the negative side of the DC supply. In that way, each terminal to terminal or line to line voltage can be either positive or negative. By controlling the switching sequence of the IGBTs, the control provides a simulated 3-phase sine voltage with frequency and voltage control. The waveform is composed of DC pulses and doesn't look too much like a sine wave, but the effective value is a reasonably good simulation of a sine wave.

The IGBT turns on when the collector-emitter voltage is positive and greater than $V_f$ and a positive signal is applied at the gate input ($g > 0$). It turns off when the collector-emitter voltage is positive and a 0 signal is applied at the gate input ($g = 0$) as we are doing in initial stage.

The IGBT device is in the off state when the collector-emitter voltage is negative. Note that many commercial IGBTs do not have the reverse blocking capability. Therefore, they are usually used with an anti-parallel diode. The IGBT block contains a series $R_s$-$C_s$ snubber circuit, which is connected in parallel with the IGBT device (between terminals C and E).

Each IGBT has a diode in parallel but positioned to conduct current in the opposite direction. The "anti-parallel" diodes conduct the portion of the motor current waveform that lags the voltage.

A current is passed through one of the stator windings; torque is generated by the tendency of the rotor to align with the excited stator pole. , if the poles a1 and a2 are energized then the rotor will align itself with these poles. Once this has occurred it is possible for the stator poles to be de-energized before the stator poles of b1 and b2 are energized. The rotor is now positioned at the stator poles b. This sequence continues through c before arriving back at the start. This sequence can also be reversed to achieve motion in the opposite direction. This sequence can be found to be unstable while in operation.

The direction of the torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flowing through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase’s excitation with the rotor position. The amount of current flowing through the SRM winding is controlled by switching on and off power electronic devices, IGBTs here, which can connect each SRM phase to the DC bus.

While Designing Soft switching circuits we need to keep in mind the following points:

- For the purpose of the phase current control, it is necessary to modulate the phase voltage. This is especially important at low speed, when the motor back-emf is low.
- The voltage gain of the converter should be maximum possible in order to extend the constant power operation mode and increase the maximum speed.
- Large fall time of phase current results in negative torque and this time can be reduced if demagnetizing voltage is as high as possible.
- It is necessary, at the same time, to control current in one phase and force demagnetizing of some other phase of the motor. This is crucial for reduction of the torque ripple.
- Converter has to be single rail in order to reduce the voltage stress across the semiconductor switches.
- The power converter must not require bipolar windings or rely upon the motor construction.
- A low number of semiconductor switches is desirable.

Phase current in IGBT based power converter is controlled by selecting from three possible states:

- Both switches in a phase leg are on, and phase is energized from power supply (200v) here (magnetizing stage).
- Both switches in a phase leg are off. Phase current commutates to the diodes and decays rapidly (demagnetizing stage).
- Only one of the switches is off. The voltage across winding is near zero and phase current decays slowly (freewheeling).

Experimental investigation is based on a three-phase 6/4 SRM with stator and rotor pole widths equal to 36 degree. The air- gap and the rotor length are 0.3 mm and 50.2 mm, respectively, and the per-phase winding resistance is 4.

**The switching states of IGBT's**

**(A)** Magnetizing stage (Phase1)

**(A1)** Q1- and Q+ are on (IGBT 3, 1), **(A2)** Q1 + and Q- are on (IGBT (3, 2)

It should be noted at this point that these two states lead to two possible directions of the phase current. This means that the current in the winding is bipolar, rather than unipolar.

a) **Magnetization Stage**

The SRM under consideration is of short pitched design, where torque is produced entirely due to the variation of the self-inductance with rotor position, it is obvious that the same torque can be generated with both unipolar and bipolar currents. In both A1 and A2 switching states, full DC bus voltage is available across the winding for magnetization stage.

b) **Demagnetizing Stage**

IGBT Q- is on (A1 magnetizing) or Q+ is on (A2 magnetizing). The switches in off-going phase leg are off. Phase current commutates to diodes and decays rapidly

c) **Freewheeling**

The winding can be short-circuited by either turning off switches (Q+, Q-) or (Q+, Q-). Phase current decays slowly.

- V- Stator voltages
- Flux- Flux linkage
- I-Stator currents
- Te- Electromagnetic torque
- w- Rotor speed
- theta- rotor position

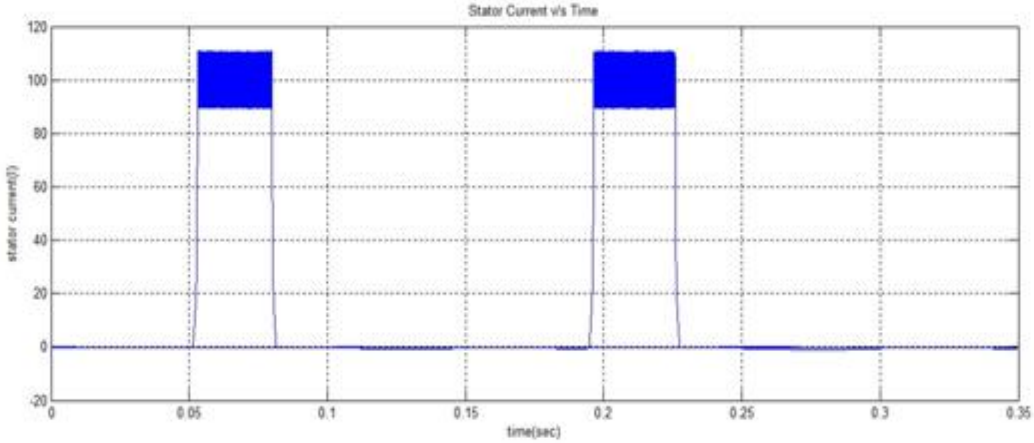


Figure 4.3: Stator Current Using Mosfet Converter Model

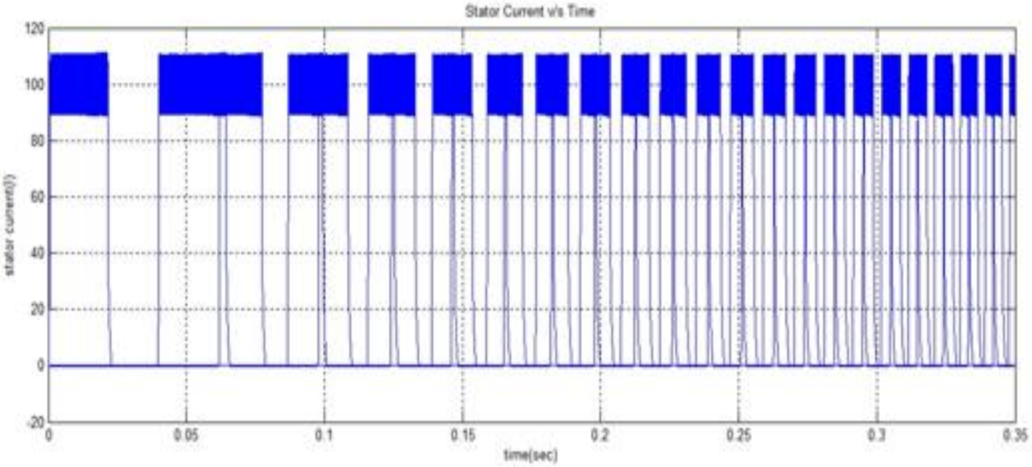


Figure 4.4: Stator Current Using Soft Switching IGBT Converter Model

We compared the outputs of stator current of both the MOSFET converter model and IGBT soft switching converter model. Maximum current in both the model`s output is 110Amp. We observed the delay in MOSFET converter model from 0 to 0.05 seconds and it needs much time to switching as shown in figure. But there is no delay in soft switching converter where we use IGBT. In IGBT used soft switching converter the output of stator current is stable from starting and it needs much less time to trigger as compared to MOSFET converter model.

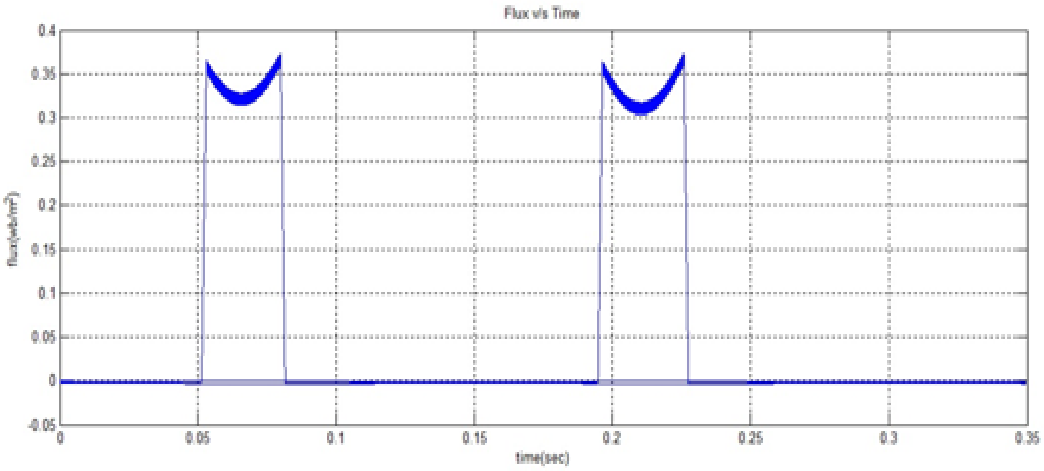


Figure 4.5: Flux Linkage Using Mosfet Converter Model

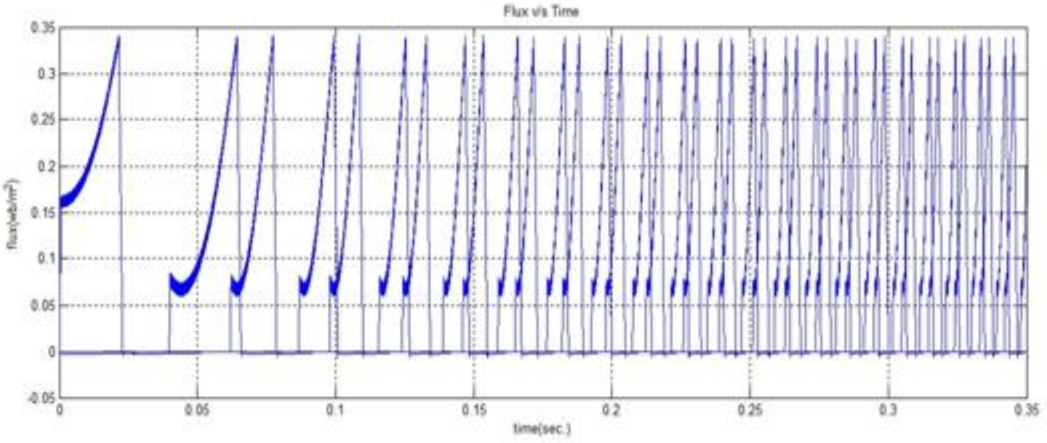


Figure 4.6: Flux Linkage Using Soft Switching IGBT Converter Model

Flux linkages of MOSFET used converter model and IGBT used soft switching converter model is compared. In MOSFET used converter model there is delay from 0 to 0.05second and MOSFET need much time to trigger the next phase. But in IGBT soft switching converter model there is no delay and output is stable initially. It needs some time to trigger the next phase as shown in figure.

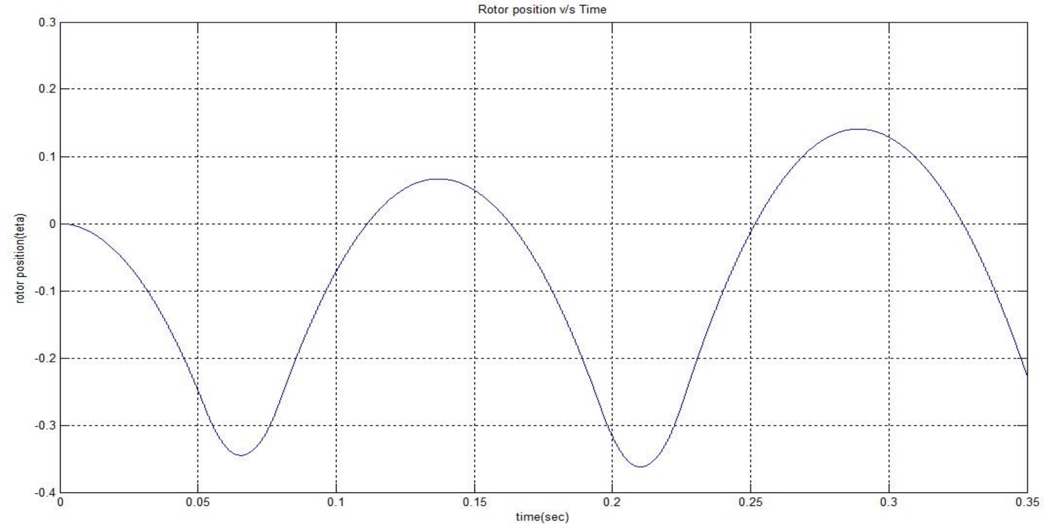


**Figure 4.7: Rotor Position (Teta) Using Mosfet Converter Model**

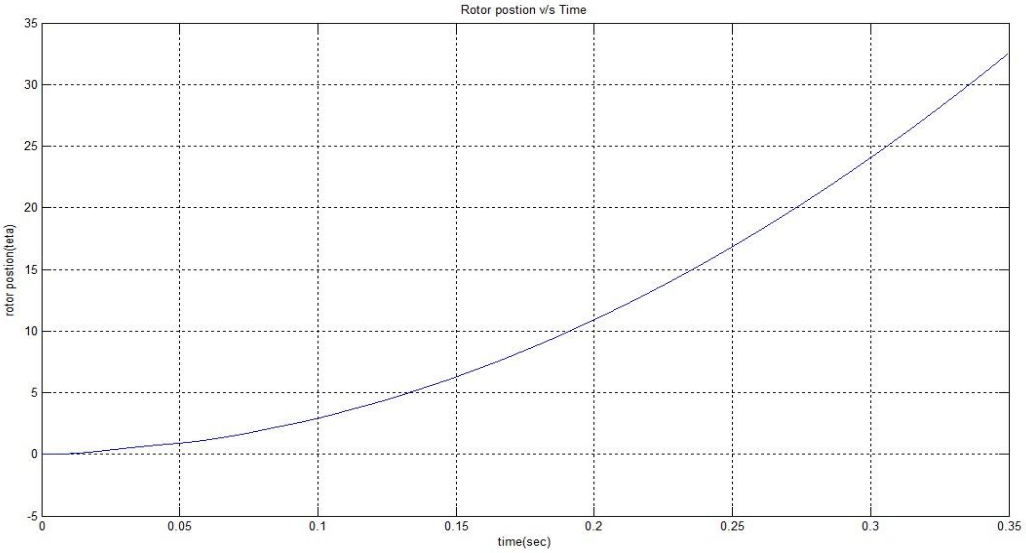


**Figure 4.8: Rotor Position (Theta) Using Soft Switching IGBT Converter Model**

On compared the outputs of rotor position of the converter model and soft switching converter model we observed that the theta (rotor position) in converter model got negative slope from 0 to 0.05 second after that MOSFET is triggered and got positive slope as shown in figure and again negative slope before the triggering of next phase. But in soft switching converter model the rotor position teta increases as time in second increases.

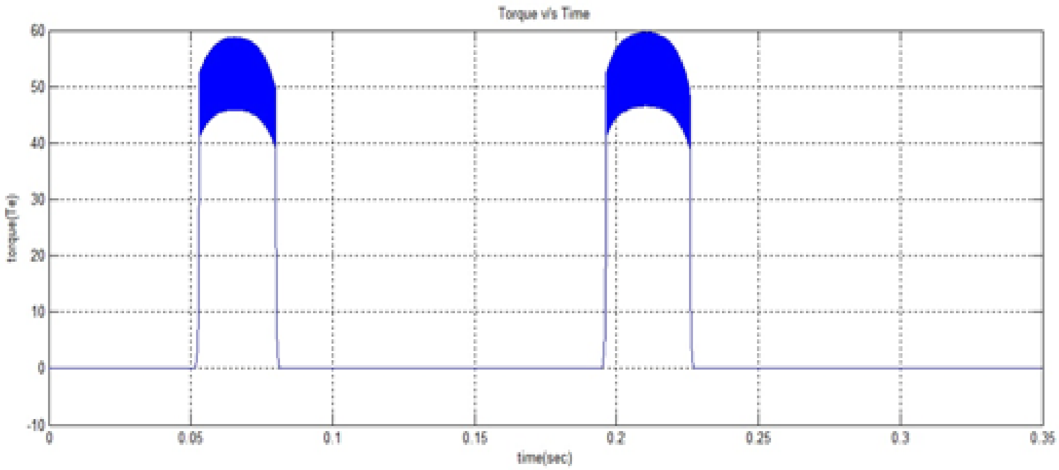


Figure 4.9: Electromagnetic Torque Using MOSFET Converter Model

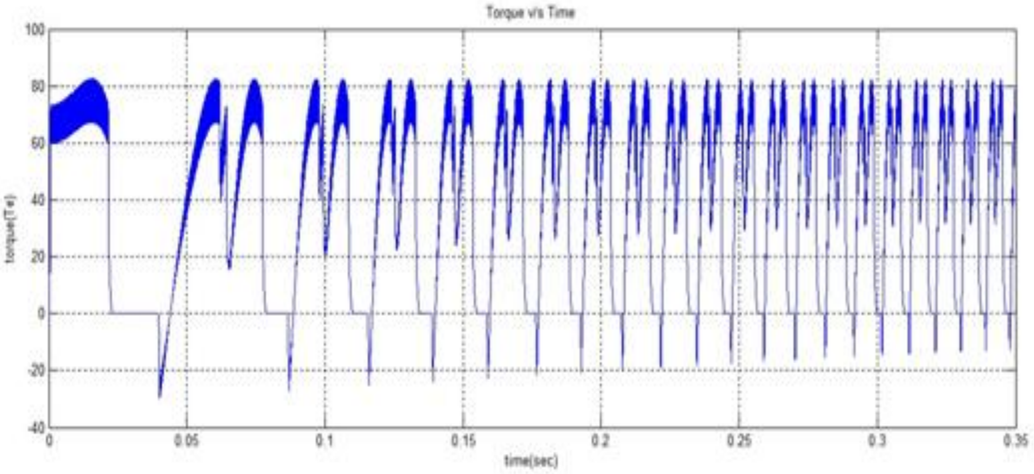


Figure 4.10: Electromagnetic Torque Using Soft Switching IGBT Converter Model

The two models MOSFET converter model where the hard switching is used and the IGBT soft switching converter model were subjected to be compared. It was concluded from the above results there was a delay from 0 to 0.05 second in MOSFET converter model and the maximum torque is at 60. There was no delay in IGBT soft switching converter model as it gets started initially and the maximum torque is at 80. Due to back emf, we saw the negative torque. Stability was seen from initial point.

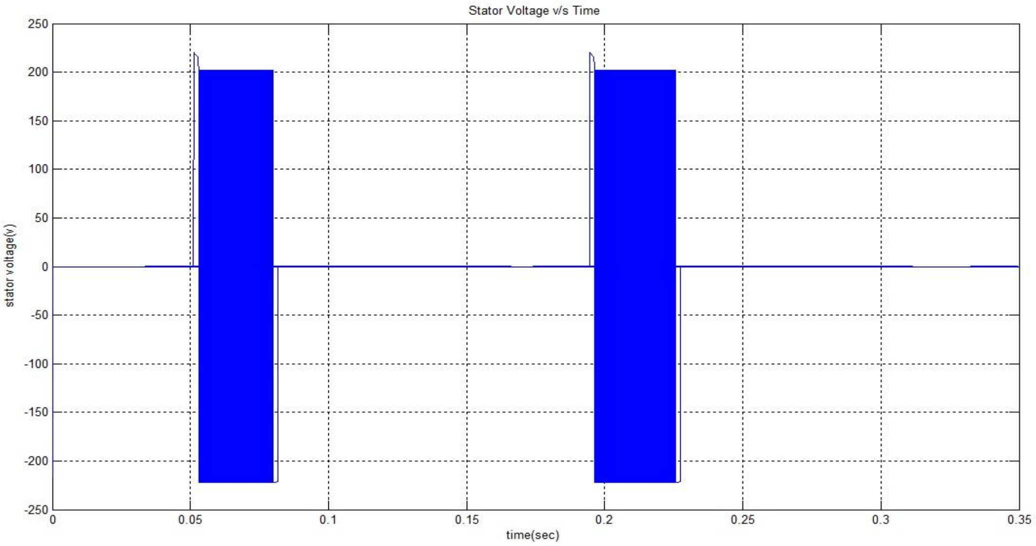


**Figure 4.11: Stator Voltage Using Mosfet Converter Model**

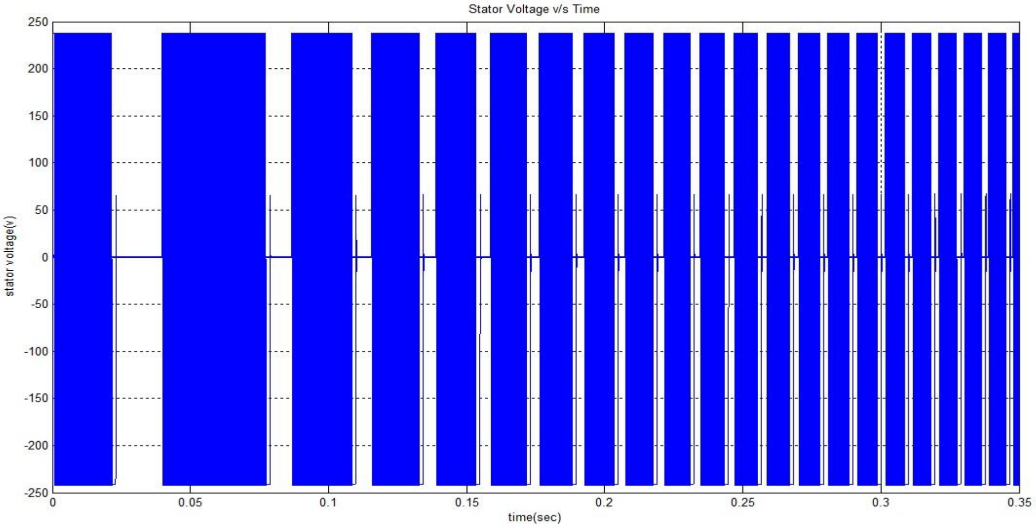


**Figure 4.12: Stator Voltage Using Soft Switching IGBT Converter Model**

The devices were placed under observations of stator voltage of both converter model and soft switching converter model. We concluded that there is a delay from 0 to 0.05 second. In that period there is no stator voltage as seen in figure. But in IGBT soft switching converter model there is no delay. As shown in figure it needs much less time to trigger the next phase as compared to MOSFET converter model.

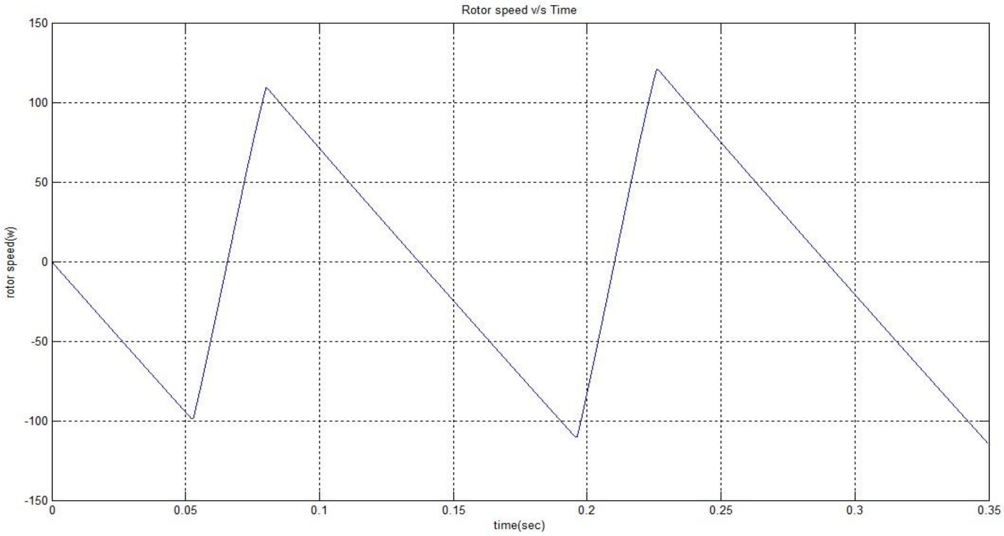


**Figure 4.13: Rotor Speed Using MOSFET Converter Model**

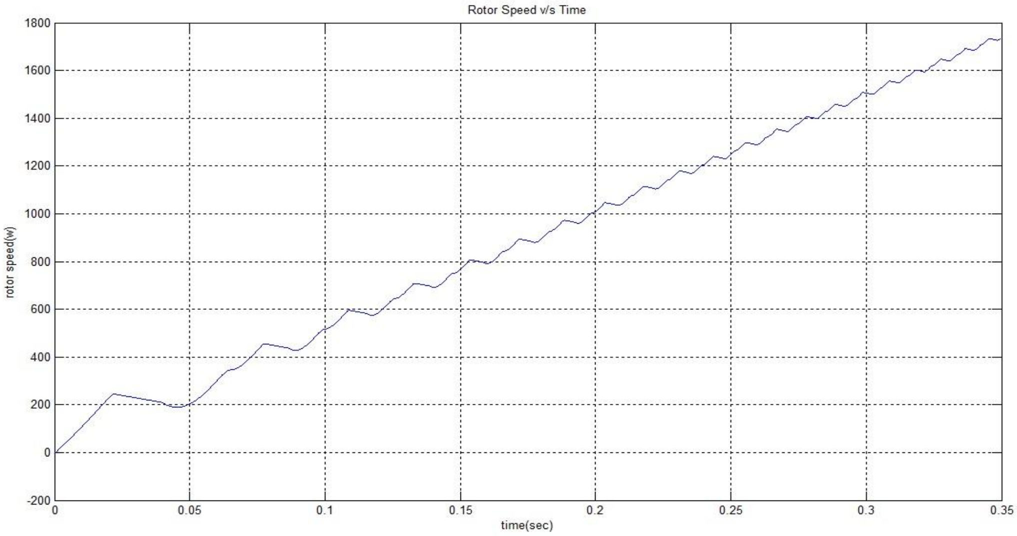


**Figure 4.14: Rotor Speed Using Soft Switching IGBT Converter Model**

Rotor speed in MOSFET using converter model got negative slope from 0 to 0.05 second and got positive slope after the triggering of MOSFET. We observed that the output of rotor speed of soft switching converter model increases as the time in second increases. The maximum speed of IGBT soft switching converter model was more than the MOSFET converter model as seen in given figure.

# CHAPTER 4

# CONCLUSION AND FUTURE SCOPE OF WORK

## 4.1 CONCLUSION

In this thesis, we proposed and implemented a novel soft switching converter topology for a switched reluctance motor drive. The operating principle of the SRM was described and the research being done in the field of SRM converters was discussed. The scarcity of research in the field of soft switching converters for SRM motors was identified. A novel soft-switching topology with IGBT was presented. It can be stated that soft switching with IGBT is better than MOSFET converter topology. With MOSFET we did not get clamped outputs for voltage, torque and current as MOSFET works as bipolar junction transistor and perform hard cut off. We observed the delay in MOSFET converter model but there is no delay in IGBT soft switching converter model and get clamped outputs. Hence, the proposed topology has been successfully implemented and its effectiveness has been verified.

## 4.2 FUTURE SCOPE

One of the major problems in SRM drives is the high torque ripple. Any work done to minimize this torque ripple would be interesting and challenging. Furthermore, the effect of the proposed soft switching topology on torque ripples. Also we can increased the motor speed with faster rate of rise and fall for the phase current, which permits the motor to operate at higher speeds. Also we use the capacitor, capacitor is charged through the resonant circuit which consists of the motor phase winding inductance during the phase turn off interval. This capacitor is discharged during the next working stroke into the appropriate phase winding.

# REFERENCES

[1] http://en.wikipedia.org/wiki/Switched_reluctance_motor.

[2] http://dr-ooi.com/Basic_of_SR_Motor.htm.

[3] Atsuhiko Sakurai, “Sliding Mode Control of Switched Reluctance Motors”, thesis, University of Toronto, 2001.

[4] Michael T. Direnzo, “Switched Reluctance Motor Control–Basic Operation, Application report, pp. 3-20, Feb 2000.

[5] Krishnan, R., M. Abouzeid, and X. Mang, “A Design Procedure for Axial Field Switched Reluctance Motors”, in Conf. Rec. of the 1990 IEEE IAS Ann. Mtg., Vol. 1, pp. 241–246, 1990.

[6] Chatratana, S. and H.R. Bolton, “Investigations into Small, Single Phase Switched Reluctance Motors”, in Proc. IEEE Conf. on Small and Special Electrical Machines, pp. 99–102, 1981.

[7] Deshpande, U.S., J.J. Cathey, and E. Richter, “A High Force Density Linear Switched Reluctance Machine”, IEEE IAS Ann. Mtg., Vol. 1, Toronto, Canada, pp. 251–257, 1993.

[8] Lee, Byeong-Seok, Han-Kyung Bae, Praveen Vijayraghavan, and R. Krishnan, “Design Of A Linear Switched Reluctance Machine”, IEEE IAS Ann. Mtg., Phoenix, AZ, pp. 2267–2274, 1999.

[9] Liu, C.T. and Y.N. Chen, “On the Feasible Polygon Classifications of Linear Switched Reluctance Machines”, IEEE Int. Electric Machines and Drives Conf. Rec., Milwaukee, WI, pp. TB1/11.1–11.3, 1997.

[10] R. Krishnan, Switched Reluctance Motor Drive: Modeling, simulation, Analysis, Design and application, Magna Physics Publishing, 2001.

[11] R. Krishnan, M. Abouzeid and X. Mang, “A Design Procedure for Axial Field Switched Reluctance Motors”. IEEE conference on industry application society annual meeting, Vol. 1, pp. 241-246, 1990.

[12] U.S. Deshpande, J.J. Cathey and E. Richter, “A High Force Density Linear Switched Reluctance Machine”. IEEE conference on industry application society annual meeting, Vol. 1, pp. 251-257, 1993.

[13] Byeong-Seok Lee, Han-Kyung Bae and Praveen Vijayraghavan, “Design of a Linear Switched Reluctance Machine”. IEEE Transactions on industry applications, Vol. 36, pp. 1571-1580, 2000.

[14] Cheng-Tsung Liu and Yan-Nan Chen, “On the Feasible Polygon Classifications of Linear Switched Reluctance Machines”. IEEE international conference on electric machine and drives, pp. TB1/11.1-TB1/11.3, 1997.

[15] M. Ehsani, I. Husain, K. R. Ramani and J. H. Gallow, “Dual Decay Converter for Switched Reluctance Motor Drives In Low Voltage Applications”. 22nd annual IEEE power electronics specialists conference, pp. 620-624, 1991.

[16] Do-Hyun Jang, Iqbal Hussain and Mehrdad Ehsanid, “The Efficiency And Performance Analysis Of Dual Decay Converter for Switched Reluctance Motor Drives”. IEEE industry applications society annual meeting, Vol. 1, pp. 658-664, 1994.

[17] Geun-Hie Rim, Won-Ho Kim, Eun-Soo Kim, Ki-Chul Lee, “A Chopping-Less Converter for Switched Reluctance Motor With Unity Power Factor And Sinusoidal Input Current”. The 25th annual IEEE power electronics specialists’ conference, Vol. 1, pp. 500-507, 1994.

[18] R. Krishnan, “A Novel Converter Topology for Switched Reluctance Motor Drives”. 27th annual power electronics specialists conference, Vol. 2, pp. 1811-1816, 1996.

[19] Geun-Hie Rim, Won-Ho Kim and Jung-Goo Cho, “ZVT Single Pulse Current Converter for Switched Reluctance Motor Drives”. 11th annual applied power electronics conference and exposition, Vol. 2, pp. 949-955, 1996.

[20] T.W. Ching, K.T. Chau and C.C. Chan, “A Novel Zero-Voltage Soft-Switching Converter For Switched Reluctance Motor Drives”. 24th IEEE annual conference on industrial electronics society, Vol. 2, pp. 899-904, 1998.

[21] A. Consoli, A. Testa, **N.** Aiello, F. Gennaro and M. Lo Presti, “Unipolar Converter for Switched Reluctance Motor Drives with Power Factor Improvement”. 16th annual applied power electronics conference and exposition, Vol. 2, pp. 1103-1108, 2001.

[22] Do-Hyun Jang, “The New Converter Topology using Half Bridge Inverter for the Switched Reluctance Motor Drives”. IEEE international symposium on industrial electronics, Vol. 2, pp. 1387-1392, 2001.

[23] Tilak Gopalarathnam and Hamid A. Toliyat, “A High Power Factor Converter Topology for Switched Reluctance Motor Drives”. 37th IAS annual industry applications conference, Vol. 3, pp. 1647-1652, 2002.

[24] M. Hiller, R. Marquardt, “A New Converter Concept for Switched Reluctance Motor Drives With Multiple Energy Sources”. The 5th international conference on power electronics and drive systems, Vol. 2, pp. 1235-1240, 2003.

[25] P. Bazzaz, Ebrahim Afjei and Hamid A. Toliyat, “A Hybrid Converter for High Speed Operation of Switched Reluctance Motor Drives”. IEEE international conference on electric machines and drives, pp. 71-71, 2005.

[26] R. Jeyabharatlil, P. Veena and M. Rajaram, “A New Converter Topology for Switched Reluctance Motor Drives”. IEEE annual conference, pp.580-584, 2005.

[27] Chen Hao and Ahn Jin-Woo, “A Novel Combined Control For Switched Reluctance Motor Drive”. Canadian conference on electrical and computer engineering, 2002, Vol. 1, pp. 246-250, 2002.

[28] Wanderlei Marinho Da Silva and Clovis Goldemberg, “A New Three Phase Full-Bridge C-dump Converter Applied to Switched Reluctance Motor Drives”. 36th IEEE power electronics specialist’s conference, pp. 2684-2690, 2005.

[29] Yuen-Chung Kim, Yong-Ho Yoon, Byoung-Kuk Lee, Hack-Seong Kim and Chung-Yuen Won, “Control Algorithm for Four-Switch Converter of Three-Phase Switched Reluctance Motor”. 37th IEEE power electronics specialists conference, pp. 1-5, 2006.

[30] H. Chen, Y.Zhu and D. Zhang, “Design of the Power Converter for 600KW Switched Reluctance Motor Drive”. 33rd IEEE annual power electronics specialists conference, Vol. 4, pp. 1913-1918, 2002.

[31] Hong-Je Ryoo, Won-Ho Kim, Geun-Hie Rim, Wook Kang, Ji-Ho Park and Ghung-Yuen Won, “A New Split Source type Converter for Switched Reluctance Motor Drives”. 29th IEEE annual power electronics specialists conference, Vol. 2, pp. 1290-1294, 1998.

[32] M. Dahmane, F. Meibody-Tabar, F-M. Sargos, “An Adapted Converter for Switched Reluctance Motor/generator for High Speed Applications” IEEE industry applications conference, Vol. 3, pp. 1547-1554, 2000.

[33] S. Woothipatanapan, P. Chancharoensook and A. Jangwanitlert, “Efficiency Improvement of Converter for Switched Reluctance Motor Drives at Low Speed Operation”. International conference on power electronics and drive systems, pp. 488-493, 2009.

[34] Natália S. Gameiro and A. J. Marques Cardoso, “Fault Tolerant Power Converter for Switched Reluctance Drives”. 18th International conference on electrical machines, pp.1-6, 2008.

[35] Z. Nie and A. Emadi, “Integrated Converters for Switched Reluctance Motor Drives”. 4th international power electronics and motion control conference, Vol. 2, pp. 487-490, 2004.

[36] M. Krishnamurthy, B. Fahimi and C. S. Edrington, “Comparison of Various Converter Topologies for Bipolar Switched Reluctance Motor Drives”. 36th IEEE power electronics specialists conference, pp. 1858-1864, 2005.

[37] Yong-Ho Yoon, Dae-Hee Han, Se-loo Kim, Duck-Kyu Kim and Chung-Yuen Won, “Current Hysteresis Controlled Resonant C-dump Converter for Switched Reluctance Motor Drive”. 35th annual power electronics conference, Vol. 2, pp. 1329-1334, 2004.

[38] Sayeed Mir, Iqbal Husain and Malik E. Elbuluk, “Energy Efficient C-Dump Converters for Switched Reluctance Motors”. IEEE transactions on power electronics, Vol. 12, pp. 912-921, 1997.

[39] Wang Xiaoyuan, Pan Hao and Wang chuan, “New Power Converter Circuit for Switched Reluctance Motor on Intelligent Power Module”. Control and decision conference, pp. 3757-3760, 2008.

[40] K.Y. Cho and J.Y. Lim, “Power Converter Circuit for Switched Reluctance Motor Using a Flyback Transformer”. IEE electric power applications, Vol. 150, pp. 88-96, 2003.

[41] L.Morel, H.Fayard, R. Vives Fos, A. Galindo and G Abba, “Study of Ultra High Speed Switched Reluctance Motor Drive”. IEEE Industry conference, Vol. 1, pp. 87-92, 2000.

[42] Feel-Soon Kang, Jung-Han Lee, Cheul-U Kim and Sung-Jun Park, “Single Stage Power Factor Corrected Switched Reluctance Motor”. 28th IEEE annual conference of industrial electronics society, Vol. 2, pp. 1055-1059, 2002.

[43] S.J. Watkins, J. Corda and L. Zhang, “Multilevel Asymmetric Power Converter for Switched Reluctance Motor”. International conference on power electronics machines and drives, pp. 195-200, 2002.

[44] Jianing Liang, Seung-Hun Seok, Dong-Hee Lee and Jin-Woo Ahn, “Novel Passive Boost Converter for Three-Phase Switched Reluctance Motor”. International conference on electrical machines and systems, pp. 1-5, 2009.

[45] K.J. Tseng and J. Wang, “A New Hybrid C-dump and Buck-fronted Converter for Switched Reluctance Motor”. 25th IEEE annual conference of the industrial electronics society, Vol. 3, pp. 1109-1114, 1999.

[46] Luo Jianwu, Zhan Qionghua, “A Novel Soft-Switching Converter for Switched Reluctance Motor: Analysis, Design and Experimental Results”. IEEE international conference on electric machines and drives, pp. 1955-1961, 2005.

[47] L.G.B.Rolim, W.I.Suemitsu, E.H.Watanabe and R.Hanitsch, “Development of an Improved Switched Reluctance Motor Drive using A Soft-Switching Converter”. IEE proceeding electric power applications, Vol. 146, pp. 488-494, 1999.

[48] Levi P.B. de Oliveira, Edison R. da Silva, Ant Bnio M. N. Lima, and Cursino B. Jacobina, “New Soft-Switched Power Converter Topologies for Variable Reluctance Machine Drives”. 30th Annual IEEE conference on power electronics specialists, Vol. 2, pp. 826-831, 1999.

[49] Patrick C. K. Luk. Ken P. Jiniipim, “A Novel Switching Method for Switched Reluctance Motors”. The 4th international conference on power electronics and motion control. Vol. 3, pp. 1277-1281, 2004.

[50] Mohammad Reza Yousefi, Khalil Rahimi and Majid Pakdel, “A Novel Two-Quadrant Soft-Switched Converter”. IEEE eurocon, pp. 823-826, 2009.

[51] J.D. Van Wyk, “Power Electronic Converters for Motion Control”. Proceedings of the IEEE, Vol. 82, pp. 1164-1193, 1994.

[52] Fred C. Lee, “High-Frequency Quasi-Resonant Converter Technologies”. Proceedings of the IEEE, Vol. 76, pp. 377-390, 1988.

[53] Vorgelegt Von, “Investigation of a Drive System: Soft-Switching Converter and Switched Reluctance Motor”, thesis, university of Berlin, 1997.

[54] R.W. De Doncker and J.P. Lyons, “An Auxiliary Quasi-Resonant DC Link Inverter for Switched Reluctance Machines”. 22nd annual IEEE conference on power electronics specialists, pp. 248-253, 1991.

[55] Hoang Le-Huy, Karim Slimani and Philippe Viarouge, “A Current-Controlled Quasi-Resonant Converter for Switched-Reluctance Motor”. 16th annual IEEE transactions on industrial electronics, Vol. 38, pp.355-362, 1991.

[56] S. S. Park and T.A. Lipo, “New Series Resonant Converter for Variable Reluctance Motor Drive”. 23rd annual IEEE conference on power electronics, Vol. 2, pp. 833-838, 1992.

[57] Geun-Hie Rim, Won-Ho Kim and Jung-Goo Cho, “ZVT Single Pulse-Current Converter for Switched Reluctance Motor Drives”. Eleventh annual applied power electronics conference and exposition, Vol.2, pp.949-955, 1996.

[58] Tatsuya Uematsu and Richard G. Hoft, “Resonant Power Electronic Control of Switched Reluctance Motor for Electric Vehicle Propulsion”. 26th annual IEEE power electronics specialists conference, Vol. 1, pp. 264-269, 1995.